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Ship Navigation Simulation Study, Houston-Galveston Navigation Channels, Texas

Report 5
Executive Summary Report

by *Dennis W. Webb, J. Christopher Hewlett, Larry L. Daggett*

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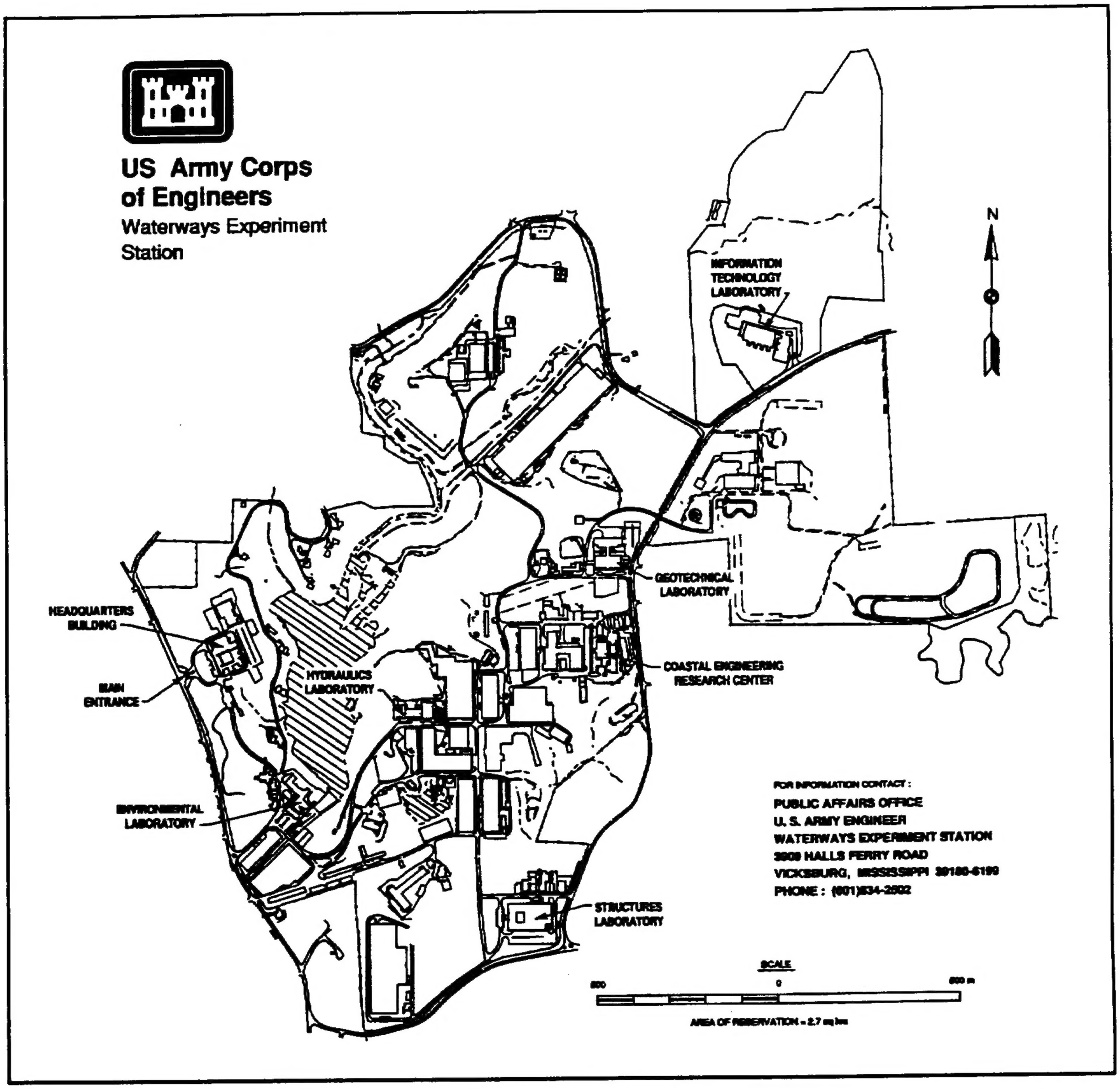

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Contents

Preface

This investigation was performed by the Hydraulics Laboratory of the U.S. Army Engineer Waterways Experiment Station (WES) for the U.S. Army Engineer District, Galveston (SWG). The study was conducted with the WES research ship simulator during the period April 1990-June 1991. SWG provided survey data of the prototype area. Current modeling was conducted by the Estuarine Processes Branch, Estuaries Division, Hydraulics Laboratory. This is Report 5 of a series. Reports 1 and 2 discuss the navigation study for the bay and bayou segments, respectively, of the Houston Ship Channel. Report 3 presents the results for the Galveston Ship Channel and Houston-Galveston Entrance Channels, and Report 4, the Houston Ship Channel-Gulf Intracoastal Waterway Intersection.

The investigation was conducted by Messrs. Dennis W. Webb and J. Christopher Hewlett of the Navigation Branch, Waterways Division, Hydraulics Laboratory, under the general supervision of Messrs. Frank A. Herrmann, Jr., Director of the Hydraulics Laboratory; Richard A. Sager, Assistant Director of the Hydraulics Laboratory; M. B. Boyd, Chief of the Waterways Division; and Dr. Larry L. Daggett, Chief of the Navigation Branch. Ms. Donna Derrick and Mr. Keith Green, Civil Engineering Technicians, Navigation Branch, assisted in the study. This report was prepared by Mr. Webb, Mr. Hewlett, and Dr. Daggett.

Acknowledgment is made to Dr. Thomas Rennie and Mr. Al Meyer, Engineering Division, SWG, for cooperation and assistance throughout the investigation. Special thanks go to the Houston Pilots Association for participating in the study.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
knots (international)	0.5144444	meters per second
miles (U.S. statute)	1.609347	kilometers

1 Introduction

The Houston-Galveston Navigation Channels are located along the coast of the Gulf of Mexico in eastern Texas (Figure 1). Channels in this vicinity include the Entrance Channel, the Bar Channels (Bolivar Roads area), Galveston Channel, the Texas City Channel, the Gulf Intracoastal Waterway (GIWW), and the Houston Ship Channel (HSC), which begins at the Bolivar Roads Channel, traverses Galveston Bay, and ends in Houston, TX. Only the entrance channels, the Galveston Channel, and the section of the HSC up to Boggy Bayou are included in the improvement project. This report summarizes the navigation studies conducted on these channels to allow larger, deeper drafted vessels to call at the ports of Houston and Galveston. These studies were conducted using the U.S. Army Engineer Waterways Experiment Station (WES) ship/tow simulator during the period 1991 to 1993. This review of the navigation studies will start from the Gulf of Mexico and progress inland.

Existing Conditions

Channel descriptions

Entrance channels. The Houston-Galveston entrance channels (Figure 2) comprise a series of straight reaches: the Entrance Channel, the Outer Bar Channel, the Inner Bar Channel, and the Bolivar Roads Channel. These channels, which link the Houston, Galveston, and Texas City Channels with the Gulf of Mexico, are presently 40 ft[1] deep[2] and 800 ft wide. This is the only portion of the project under the joint jurisdiction of both the Galveston/Texas City Pilots Association and the Houston Pilots Association.

Galveston Channel. The existing Galveston Channel (Figure 2) is 40 ft deep and 1,100 ft wide and is served by the Galveston/Texas City Pilots Association.

Intracoastal Waterway. The GIWW (Figure 2), which accommodates many users, including tow/barge traffic and small commercial and recreational

[1] A table of factors for converting non-SI units of measurement to SI units is found on page v.

[2] All depths are below mean low tide.

boats, is 12 ft deep and 125 ft wide. Some tow captains calling at Houston do so frequently, while others may call infrequently and are not as familiar with the waterway.

Houston Ship Channel. The HSC consists of about 65 miles of improved deep-draft channels, transecting the Galveston Bay from Bolivar Roads into the city of Houston. The present channel is 40 ft deep and 400 ft wide for most of its length. For simulation purposes, the HSC was divided into two distinct segments. The bay segment (Figure 3) has three gentle bends separated by long straight reaches between Bolivar Roads and Morgans Point. The inland bayou channel section (Figure 4) is a series of curves following a meandering river pattern between Morgans Point and Boggy Bayou.

Vessel traffic. Combined, the Ports of Houston and Galveston are among the busiest in the country. Houston ship pilots reported that the number of ship movements has been approaching 1,000 per month. Because of large traffic volume, two-way traffic is required throughout the channels with frequent meeting and passing situations including overtaking slower vessels, especially tows. A wide variety of traffic uses the HSC including tankers, bulk carriers, car carriers, containerships, oceangoing tows, and pushtows with barges. Numerous refineries above Morgan's Point provide destinations for the tankers; bulk loading facilities also line the channel in the same area. Container ships call predominantly at container terminals at Morgan's Point, which is accessed via a side channel, intersecting the HSC. Containers, bulk carriers, and tankers frequently call at the Port of Galveston. Tankers containing chemical products call at the Bayport Channel, another side channel that intersects the HSC.

Channel limitations. Full and efficient use of ships is restricted due to draft limitations. Over 25 percent of grain and 85 percent of petroleum are transported in vessels with design drafts greater than 40 ft. The pilots evaluate meeting and passing of vessels with a combined beam greater than 251 ft on a per-case basis. These situations are usually restricted to daylight and/or may require two pilots onboard one or both of the vessels.

Navigation difficulties

Several sites in this project cause navigation difficulties to vessels transiting the area.

Crosscurrents in Gulf. Crosscurrents in the Gulf of Mexico are a problem to local pilots for two reasons. First, vessels experiencing the effects of crosscurrents in the Entrance Channel must steer at an angle into the currents to transit the reach. Therefore the vessel is navigating at an angle in the channel, which reduces the channel width available to other vessels. Second, ships are not affected by these crosscurrents while they are protected by the Galveston jetties. The channel has a bend at the end of the jetties, between the Entrance Channel and the Outer Bar Channel. Therefore, as the ship exits the

jetties, the bow of an outbound vessel is hit by crosscurrents while its stern is not, which causes the vessel bow to swing in the direction of the current. When the bow of the inbound ship enters the portion of the channel protected by the jetties, the crosscurrents are still pushing the stern, which causes the vessel stern to swing in the direction of the current. Crosscurrents from the north (which push the vessel south) are referred to by the local ship pilots as a Freeport set, and crosscurrents from the south (which push the vessel north) are known as a Sabine set. Sabine and Freeport are ports located north and south of Galveston, respectively. For an inbound ship, a Sabine set would cause the ship to turn into oncoming traffic at the jetties, while a Freeport set would make the turn at the jetties more difficult.

Turning in Galveston Channel. Vessels turning in the Galveston Channel can be subjected to strong crosscurrents when broadside in the channel. Flood currents are of particular concern because there is a danger that the vessel might be swept into the Pelican Island Bridge, located at the west end of the channel. This has occurred in the past and is of such concern that the Galveston/Texas City Pilots Association has recently installed a current meter at the bridge. Pilots can access this meter via modem from their office for immediate current information.

Turning from the HSC into Galveston Channel. Sometimes, vessels will leave Houston and call at Galveston before going to sea. Usually this is not difficult because these vessels are light loaded and therefore not restricted to the authorized channel. However, occasionally these vessels are almost fully loaded and call at Galveston to "top off" with additional grain. This is done if the elevator in Houston runs out of grain, or if the vessel is to carry a different type of grain not available at the dock in Houston. These vessels are turned in a naturally deep area southeast of the intersection of the Galveston Channel and the Inner Bar Channel.

GIWW/HSC intersection. The intersection of the HSC and the GIWW is regarded as potentially dangerous because tows will block part of the ship channel while turning on the east side of the intersection. Tows westbound on the GIWW from the Bolivar Peninsula turning north inbound on the HSC present the greatest safety problem, particularly during flood tide. Tidal currents up to 3.7 fps occur during flood tide and up to 4.2 fps during ebb tide, under extreme tidal conditions. In an attempt to avoid the flood tide pushing the tow toward a shoal area located northeast of the intersection, tow captains are forced to turn their tows in the deep-draft portion of the HSC. Due to the heavy ship traffic, this creates a potentially dangerous situation. Since the ebb tide pushes the tow away from the shoal, the tow captains do not have to occupy the deep-draft portion of the HSC for as long.

Meeting/passing in Galveston Bay. Ships with beams in the neighborhood of 140 to 145 ft use the channel; however, meeting/passing of two such ships is closely monitored and controlled by pilots (especially when both are loaded) and is not allowed except under certain circumstances. On the other hand, smaller ships such as Panamax types (106-ft beams) meet and pass each

other on a regular basis. The meeting/passing maneuver utilizes both ship/ship interaction forces and bank effects and requires skill, careful control, and timing of operations. This is accomplished by the pilots of both ships closely coordinating their efforts. The meeting/passing maneuver is considered the most critical navigation concern in the bay section.

Bayou section. Navigation concerns in the bayou section include a highly constricted channel between the Cargill and Oxy-Chem facilities and three severe turns. These turns are located at the Baytown Bridge, the Exxon terminals, and the Lynchburg ferry. Meeting and passing maneuvers also occur in this section and require careful planning and control by the pilots.

Overtaking slower vessels. The overtaking and passing of larger, slower ships by smaller, faster ships occurs throughout the HSC, although much less frequently than meeting/passing. While not as critical as the meeting/passing situation, care must be used by the pilots to ensure that this action is undertaken only in areas of adequate width throughout the overtaking reach. Typically, the larger vessel is limited in how much it can slow down to allow the smaller ship to pass because it must keep enough headway to maintain steerage.

Feasibility Study Plan

Original plan

The U.S. Army Engineer District (USAED), Galveston, has proposed a phased improvement plan for the Houston/Galveston Navigation Channels. The 1987 feasibility report (USAED, Galveston, 1987) recommended a single-phase 50-ft project. The project was divided into two phases by Headquarters, U.S. Army Corps of Engineers. This plan consists of Phase I and Phase II improvements. The Phase I plan will deepen the channels to a depth of 45 ft while the Phase II plan will deepen the channels to a depth of 50 ft.

Entrance/bar channels. Phase I entrance channels (Figure 5) are to be 47 ft deep, and the Phase II channels are to be 52 ft deep (Figure 6). The additional 2 ft of depth is to allow for the vertical motion of the vessel due to wave action. The existing Entrance Channel will have to be extended 4 miles for Phase I and an additional 7 miles for Phase II (for a total of 11 miles), out to the 47- and 52-ft contours, respectively. Phase I will remain at the existing channel width of 800 ft, while a portion of the Phase II extension will narrow to 600 ft. Bend wideners were installed in the simulation database for both phases of the proposed improvements.

Galveston Ship Channel. The Phase I Galveston Channel will be deepened to 45 ft and realigned to a 450-ft width (Figure 7). The Phase II channel will be 50 ft deep with the same width and alignment as the Phase I channel.

GIWW/HSC intersection. In order to allow inbound tows to turn from the GIWW toward Houston without entering the deep-draft portion of the HSC, wideners on both sides of the intersection were proposed (Figure 8). The depth of the channel wideners would be the same as the existing GIWW, 12 ft.

HSC-Galveston Bay segment. The Phase I channel would be a minimum of 530 ft wide and 45 ft deep. The Phase II channel would be a minimum of 600 ft wide and 50 ft deep. Minor realignment was planned near Redfish Reef.

HSC-bayou segment. The Phase I channel would be a minimum of 530 ft wide and 45 ft deep. The Phase II channel would be a minimum of 600 ft wide and 50 ft deep. Realignment of the channels was proposed (Figure 9), with the Phase I and Phase II channels having the same center line.

Modifications

Prior to testing, several modifications were made to the plans as recommended in the feasibility study. These changes were the result of either pilot comments and follow-up evaluations, examination of the feasibility plan, or preliminary testing of the feasibility plan.

Entrance channels. The Outer Bar Channel was widened 100 ft on the north side (Figure 10). The pilots requested this change to allow an inbound vessel additional room to recover from the Gulf crosscurrents as it enters the jetty area. The other channel widths were not changed.

Galveston Channel. Preliminary tests of the Phase I Galveston Channel revealed that the plan required modification prior to the full testing program. During preliminary test runs, bulk carriers outbound from Houston were unable to safely make the turn into the Galveston Channel. Preliminary tests of the bulk carrier outbound from Galveston in the feasibility study channel showed the pilots had some problems keeping their vessels in the narrowed and realigned channel. Of additional concern to the pilots was the fact that the 450-ft-wide channel ran alongside the docks between piers 10 and 36. With the 450-ft channel alongside the docks, ships traveling at 4 knots or faster run a significant risk of pulling docked ships away from the docks, resulting in broken mooring lines and potential damage to both ships and docks. Since Galveston Channel has strong currents, the pilots must keep a headway of at least 4 knots when heading in the same direction as the tidal currents to maintain steerage. Pilots also had a difficult time determining their position in the curved, 450-ft-wide channel. Also, the feasibility alignment did not provide a turning area for vessels drafting more than allowable for the existing 40-ft channel. For example, ships partially loaded with grain from Houston may enter Galveston to complete loading with more grain (possibly of a different type or quality) before departing.

In response to concerns about the feasibility study of the Galveston Channel alignment, an new alignment was designed (Figure 11). This alignment took advantage of a naturally deep area just north of the south Galveston jetty to provide a transition or funnel from the Inner Bar Channel and the Bolivar Roads Channel into the Galveston Channel. Additionally, the reach between Pier 10 and Seawolf Park was straightened so that outbound ranges could be positioned in Galveston Bay. These ranges will assist the pilots in accurately positioning the ship in the deepened channel, which is not symmetrically placed between the land/pier line. These ranges would be used as rear ranges for inbound ships.

GIWW/HSC intersection. The proposed improvement described in the feasibility report consisted of wideners on both sides of the intersection. After discussions with the U.S. Coast Guard (USCG) and the towing industry, the widener on the western side of the intersection was eliminated and all efforts were concentrated on the eastern side of the intersection (Figure 12). A second alternative was developed based on suggestions from the towing industry (Figure 13). This alternative consisted of a one-way cutoff channel only for tows inbound to Houston. The purpose was to allow inbound tows a smaller approach angle to enter the HSC. In order to evaluate these two designs and if necessary modify them, a pretesting exercise was undertaken.

A preliminary testing team assembled at WES for 3 days of preliminary testing. In addition to the WES staff, the team consisted of two tow captains who regularly transit the intersection of the GIWW and HSC and two USCG officers. The ship pilots were not involved since this was a preliminary design, and the design process could be done using tows only. The tow captains operated the simulator in real-time mode and gave insight to problems they were having while transiting the reach. The USCG representatives provided guidance on channel marking and channel operation. Testing was done in an iterative mode with solutions being offered to navigation problems encountered during a simulator test run, those solutions being implemented into the simulation model, and additional test runs being made to evaluate the new navigation layout.

During preliminary testing, it was agreed by all team members to omit the one-way cutoff from further consideration as a channel alternative for the following reasons:

a. The turn from the Bolivar Peninsula Channel into the cutoff was too difficult during ebb tide.

b. Deep-draft ships might experience adverse effects from the cutoff due to a change in bank effects and possible crosscurrents entering the ship channel.

c. Ships would pull water out of the cutoff as they passed, possibly causing grounding of tows in the cutoff and breaking the lines holding the barges of these tows.

d. The USCG was concerned about the operation of tow traffic in and control of a one-way cutoff channel, i.e., preventing outbound tows from using it.

At the end of preliminary testing it was unanimously decided that a modification of the eastern widener proposed in the feasibility report be used for the test program (Figure 14). This widener allowed the tows a more gradual turn into the HSC. Only three buoys would be required to mark this cutoff, as opposed to the four currently being used. In addition, it was determined that flaring the southern edge of the GIWW near the Bolivar Peninsula would allow eastbound tows safer entrance into that portion of the GIWW. The channel was flared by moving the edge of the channel 150 ft to the south and was designed as an add-on feature. It was not tested during the interactive design phase.

HSC-bay segment. The alignment proposed in the feasibility report (USAED, Galveston, 1987) was not modified prior to testing.

HSC-bayou segment. WES proposed a redesign of the alignment of the proposed bayou segment channels (Figure 15) so that the proposed curved channel would be a series of straight reaches, to keep the new channel closer to the existing channel and to avoid encroaching on the San Jacinto State Park and a bird rookery on Alexander Island. Some aspects of the proposed redesign were based on discussions with HSC pilots and the Galveston District. The curves were replaced with the straight reaches because straight channels are generally regarded as safer to navigate. They also provide the ship handler with better knowledge of the ship's location in the channel because the buoys along a straight reach will appear in a line, and ranges allow determination of the ship's location within the channel. The channel alignment at the Baytown Bridge was chosen to allow vessels to begin their turn prior to passing through the bridge for both inbound and outbound transits. The proposed channel north of Alexander Island and west of the Exxon Terminal was widened an additional 200 ft on the north side to allow inbound vessels to move further to the north while meeting an outbound vessel. This would give the outbound ship more room to prepare for the turn south at Exxon. The existing turn is difficult for an outbound ship forced to remain on the south side of the channel. The radius of the turn is significantly decreased and the bank effects resulting from the ship's proximity to the steep channel edge will turn the ship to the north. The channel east and west of the San Jacinto River was widened to allow the ships to be aligned as straight as possible in the channel while passing through the confines of the ferry slips. The proposed channel alignment also included two overtaking areas, one located west of the San Jacinto State Park, and the other located east of Boggy Bayou. Due to the location of the Cargill and Oxy-Chem docks, the Phase II channel in this reach was limited to a width of 530 ft (Figure 16) to prevent major relocation of either of the docks and other facilities. Large ships docked on the channel side of Cargill dock can further restrict the usable channel width and require slow maneuvering speeds in this reach.

2 The Simulation Study

The navigation study was conducted using the WES Hydraulics Laboratory's ship/tow simulator facility. The study tested both Phase I and II channels for safe navigation and efficient design by comparing simulator results of the proposed channels with simulator results of the existing channels.

Design Vessels

The ship files contain characteristics and hydrodynamic coefficients for the test vessels. These data are the simulator definition of the ship, i.e., the ship model. The coefficients govern the reaction of the ship to external forces, such as wind, current, waves, banks, underkeel clearance, ship/ship interaction, and ownship controls, such as rudder and engine revolutions per minute (rpm) commands. The numerical ship models for the HSC simulations were developed by Tracor Hydronautics, Inc., of Laurel, MD (Ankudinov 1991). In addition, the bow of the ship was also seen in the visual scene by the pilot from the ship bridge. Visual images of the ship bows for all design ships had been created for previous studies at WES. The test ships were chosen based on the District's economic analysis of future shipping business and operations. Table 1 lists the particulars of the ships used in the simulations. Figure 17 shows the ships' sizes relative to the 400-ft, 530-ft, and 600-ft channels.

For most tests, the inbound vessel was the loaded tanker and the outbound vessel was the loaded bulk carrier. This reflects actual traffic entering and leaving the HSC, with oil imported in the tanker and grain exported on the bulk carrier. The only exception was a set of tests conducted with a loaded inbound tanker meeting an outbound tanker (in ballast) in Galveston Bay. It is noted that the "design ship" combination used for the existing channel simulation tests exceeds the Navigation Safety Guidelines for the bayou section of the HSC published by the Houston Ship Pilots dated 19 July 1989. The largest loaded ship allowed to pass under normal circumstances is 860 ft long and 120 ft in beam (Houston Ship Pilots 1989).

Table 1 Test Ship Characteristics				
Ship Type	Length Overall ft	Beam ft	Draft[1] ft	Test Channel
Bulk Carrier	775	106	39	Existing
Tanker	920	144	39	Existing
Bulk Carrier	971	140	44	Phase I
Tanker	990	156	44	Phase I
Tanker	990	156	Ballast	Phase I
Bulk Carrier	971	140	49	Phase II
Tanker	1,013	173	49	Phase II
Four-barge Tow	1,169	59	9	All

[1] Some tests were conducted in the HSC bay section for the same vessels with 2-ft underkeel clearance.

Facilities

It is beyond the scope of this report to describe in detail the WES ship simulator; however, a brief explanation will be made. The purpose of the WES ship simulator is to provide the factors necessary in a computer-controlled environment to allow a man-in-the-loop navigation channel design process. The simulator is operated in real-time by a pilot at a ship's wheel or issuing orders to a helmsman while in front of a screen upon which a computer-generated visual scene through the window is projected. The visual scene is updated as the ship motion model computes a new ship's position and heading resulting from manual control input based on the pilot's commands (rudder, engine throttle, and tug commands), ship hydrodynamics, and external forces. The pushtow models allow for steering and flanking rudders and independent twin engines and propellers. The external force capability of the simulator includes effects of wind, waves, currents, banks, shallow water, ship/ship interaction, and tugboats. In addition to the visual scene, pilots are provided simulated radar and other navigation information such as water depth, relative ground and water speed of the vessel, magnitude of lateral vessel motions, relative wind speed and direction, and ship's heading.

Data Collection

Reconnaissance trips

The reconnaissance trip for the HSC bayou and bay sections was conducted

during July 1990. The purpose of this trip was to observe vessel movements with the pilots and to learn about pilot concerns and navigation conditions. During the transits, the project area was photographed and videotaped. The photographs and videos were later used in conjunction with maps, charts, and aerial photographs to develop the simulator's visual scene. The reconnaissance trip for the Galveston Channel, the Houston/Galveston entrance channels, and the GIWW/HSC intersection was performed in August of 1991.

Differential global positioning system survey

On 5 November 1990, a differential global positioning system (DGPS) survey on two ships meeting and passing in Galveston Bay was performed by John E. Chance and Associates, Inc. (JECA). WES personnel accompanied JECA on both vessels to observe the DGPS procedure and to collect rudder and propeller rpm data. Two ships that were to meet each other in the Galveston Bay were boarded with the necessary equipment to record the operation. The *Sealift Atlantic* was inbound and met the outbound *New Ideal* near Redfish Reef. The characteristics of the two ships are described in Table 2.

Table 2
DGPS Ship Characteristics

Ship	Length ft	Beam ft	Bow Draft ft	Stern Draft ft
Sealift Atlantic	587	84	8	22
New Ideal	850	136	17	28

A track plot of the two ships is shown in Figure 18. Both vessels met and passed an additional vessel during data collection. The *New Ideal* met another ship near the northern end of Redfish Reef. The *Sealift Atlantic* met another ship shortly after the DGPS system was activated. Due to scale limitations, this meeting is not shown on the track plot. As can be seen in the track plot, the *New Ideal* left the authorized channel, represented by the dashed line, during both meeting/passing operations. Since the vessel was drafting a maximum of 28 ft in a 40-ft channel, it could leave the authorized channel without grounding due to the channel side slopes.

Physical model tests

In order to provide additional data for the verification of the ship/ship interaction model, a 1:100-scale physical model of a generic straight segment of Galveston Bay was constructed at WES. Two radio-controlled, free-running model ships, one 810 ft long with a beam of 106 ft drafting 36 ft, and the other 840 ft long with a beam of 138 ft drafting 36 ft, were used to model the effects of the banks and the ships meeting and passing.

An overhead video tracking system was used to record the model ship position and orientation during each test. Results from some of the physical model tests are compared to an autopilot simulated passing condition in Figure 19.

Simulation Databases

In order to simulate the study areas, it is necessary to develop information for five input databases:

a. *Channel database*. The channel database contains dimensions for the existing channel and the proposed channel modifications. It includes the channel cross sections, bank slope angle, overbank depth, initial conditions, and autopilot track-line and speed definition. The latest information available concerning existing depths, dimensions, and bank lines of the channel came from the District-furnished hydrographic survey charts of May 1986. The proposed channel depths were provided by a TABS-2 model study (Lin 1992) conducted simultaneously with the development of the simulation data bases that computed the current magnitudes and directions.

b. *Visual scene database*. The visual scene database is composed of three-dimensional images of principal features of the simulated area, including the land, aids to navigation, traffic and docked ships, docks, and buildings. Also included in the visual scene was a large vessel docked at the Cargill terminal. This ship was located on the channel side of the dock and its bow nearly reached the channel. The size and location of this vessel were obtained from an aerial photo. It was included to present a worst-case scenario for testing the reach between Cargill and Oxy-Chem.

c. *Radar database*. The radar database contains the features for the plan view of the study area. Three different ranges of 0.5 mile, 0.75 mile, and 1.5 miles were programmed to enable the pilot to choose the scale needed. A second radar screen with a 0.25-mile range was also provided. The 0.25-mile range displayed tug forces as vectors acting upon a ship icon. The magnitude and direction of the tug vector were based upon the magnitude and direction of the tug force being applied.

d. *Ship database*. The ship data file contains characteristics and hydrodynamic coefficients for the test vessels.

e. *Current database*. Current pattern data in the channel include the magnitude and direction of the current and the water depth for each cross section defined in the channel database. The tidal current was derived from the TABS-2 model study (Lin 1992). Results from this hydrodynamic model were used to develop the current databases.

Simulator current databases were prepared for both maximum ebb and flood currents for all scenarios except the bayou segment. The current database for the bayou segment of the HSC was calculated at slack tide with a freshwater inflow of 15,000 cfs from the San Jacinto River. Slack tide was chosen because, although typically small in magnitude, both the ebb and flood tides tend to dampen out the crosscurrents caused by freshwater inflow.

Validation

The simulation was validated with the assistance of pilots licensed for the HSC and the Galveston Channel. The following information was verified and fine-tuned during validation:

a. The channel definition.

(1) Bank conditions.

(2) Currents.

b. The visual scene and radar image of the study area.

(1) Location of all aids to navigation.

(2) Location and orientation of the bridges.

(3) Location and orientation of the docks.

(4) Location of buildings visible from the vessel.

To validate the reaction of the vessel to bank forces, several simulation runs were made with the vessel transiting the entire study area. The pilot gave special attention to the response of the ship to bank forces. Problem areas were isolated, and the prototype data for these areas were examined. The values for the overbank depth, the side slope, or the bank force coefficient were then adjusted. Simulation runs were then undertaken through the problem areas, and if necessary, further adjustment was made. This process was repeated until the pilot was satisfied that the simulated vessel response to the bank force was similar to that of an actual vessel passing through the same reach in the prototype.

The reaction of the vessel to current forces was verified by conducting several simulation runs over the entire study area. The pilot was instructed to pay attention to the current effects until he was satisfied that the vessel response to the currents was similar to responses experienced in real life.

The visual scene and radar image of the study area were checked during validation of the other parameters. If the pilot noticed something missing or

misplaced, this was checked against prototype information and adjusted accordingly.

Simulation Testing

Basic testing

Real-time piloted testing was conducted on the WES ship/tow simulator in Vicksburg, MS. Tests were conducted in a random order to prevent prejudicing the results due to skill gained at operating the simulator.

During each run, the ship parameters were recorded every 5 seconds. These parameters included the position of the ship's center of gravity, speed, engine rpm, heading, rudder angle, and port and starboard clearances.

Additional testing

A follow-up test program was conducted for portions of the bayou segment. These additional tests focused on the recommended channel design at Lynchburg turn and the reach near Spilmans Island. The purpose of the tests was to develop a new channel alignment to reduce the amount of dredging and relocation costs as well as to avoid historically significant areas. The channel realignments were designed using the simulator in an interactive design mode and then tested with a full test program. Also, replacing the "straight corner" bend wideners between straight channel segments with rounded wideners was tested at the District's request.

It is beyond the scope of this report to present the results and evaluations of the simulator runs conducted during this test program. A complete evaluation of all runs is available in separate report volumes for each test segment (Hewlett 1994; Webb 1994a, 1994b; and Webb and Daggett 1994).

3 Conclusions and Recommendations

The following recommendations were furnished to the Galveston District upon completion of the test program for each segment of the Houston/Galveston Channels.

Houston-Galveston Entrance Channels

The following recommendations are made for the Houston-Galveston entrance channels:

a. Based on the simulation results, the Bolivar Roads Channel, the Inner Bar Channel, the Outer Bar Channel, and the Entrance Channel should be built as tested for the Phase I channels.

b. Based on the simulation results, the Bolivar Roads Channel, the Inner Bar Channel, and the Outer Bar Channel should be built as tested for the Phase II channels. The Phase II Entrance Channel may be built as tested with the stipulation that two vessels as large as those tested not meet in the 600-ft-wide portion of this channel. However, to maintain two-way traffic throughout the Entrance Channel it is recommended that this portion of the channel be widened to 800 ft.

Galveston Channel

The following recommendations are made for the Galveston Channel:

a. The Phase I Galveston Channel should be built to a 550-ft width, and realigned near the split buoy and the split buoy relocated west of the recommended channel (Figure 20). The turning area in Galveston Channel should be extended past Pier 36 to a length of 4,500 ft. Although this is longer than any of the distances required to turn a ship

in the simulation of the Galveston Channel, the extra length is required to

(1) Allow pilots a certain amount of choice where to turn a vessel in order to account for variable factors such as the position of docked ships.

(2) Add a factor of safety to compensate for the fact that vessels in simulators do not affect the currents. Obviously, a 971-ft-long vessel turned sideways in an 1,100-ft wide channel will increase the magnitude of the current velocities.

b. The Phase II Galveston Channel should be built to the same channel alignment and dimensions as the Phase I channel, except for the additional depth.

c. The maneuvering area north of the south jetty used by partially loaded ships leaving Houston to enter the Galveston Channel should be built. The turning length provided by this area is 5,500 ft. Much of this area is naturally deep and will not require significant dredging according to the Galveston pilots. This area should be surveyed to determine existing conditions. The USCG should be contacted regarding possible aids to navigation that might better mark the area.

HSC/GIWW Intersection

Based on the simulation tests, the following recommendations are made for the intersection of the GIWW and HSC:

a. It is recommended that the intersection be widened on the east side only and that the intersection of the GIWW and HSC be widened and marked as proposed. This widener would allow inbound tows to turn north to Houston safely without encroaching into the HSC. All inbound tows operating in the proposed channel safely met and passed an outbound ship port to port. The buoy system required to mark this turn is less complex than that currently in use. Buoys were hit less often in the proposed channel resulting in a safer channel with less maintenance by the USCG. Therefore, the proposed widener will provide safer navigation conditions for the occasional as well as for the frequent user.

b. Analysis of the proposed GIWW channel flare west of Bolivar Peninsula does not lead to an unequivocal conclusion as in the case of the GIWW/HSC intersection widener. Although it allows westbound tows to turn south sooner when facing a flood tide, for the most part, the widener is designed to assist tows eastbound from Houston to enter the Bolivar GIWW channel. There were numerous cases, both for the proposed and existing channels, where either the tow went aground, hit a

buoy, or both, when trying to enter the GIWW at Bolivar. Conditions for ebb currents were somewhat better, particularly in incidents of hitting buoys, the effects on ships, and potential grounding in the HSC. However, flood current conditions were not improved much. It is important to remember that these tests were conducted with extremely strong tidal currents. All tow captains who participated in the test program stated that the currents for both ebb and flood were stronger than those they normally experience. In actual operations, if the currents are as strong as modeled, tows can wait for the currents to subside. Of course, this can be done only if they have been informed of, or can readily determine, the current conditions in time to take the necessary actions to hold up and wait.

c. Based on the track plots and the pilot's responses, widening the GIWW at Bolivar improved the maneuver even under these difficult conditions, particularly for strong ebb conditions. Therefore, it is recommended that the proposed channel be built as tested, or a pretesting program be undertaken similar to that used to design the widener at the GIWW/HSC intersection to improve the design layout. Perhaps new aids to navigation would improve the navigation results.

d. The proposed improvements to the intersection of the HSC and the GIWW and the Bolivar Peninsula portion of the GIWW result in significant increases in navigation safety in this area. The safety benefits of this project will be of equal or greater value when combined with either the existing HSC or the Phase I HSC. Therefore, it is recommended that these improvements be built as soon as possible and that they not be dependent on the proposed deepening of the HSC.

HSC Bay Segment

The following recommendations are made for the Galveston Bay portion of the HSC:

a. Based on the simulation results, the proposed channel width of 600 ft for the Phase II (50-ft) project is recommended.

b. If the Phase I channel project (45 ft) is to have a channel width of 530 ft, it is recommended that meeting/passing situations be limited to ships whose combined beams total less than 280 ft (53 percent of channel width). This criterion may result in operational restrictions being employed, e.g., holding other large ship traffic so that the channel is temporarily one-way or with restricted ship sizes traveling in the opposite direction of the large ship. These restrictions will most likely cause delays that may have to be accounted for in any economic analysis of channel improvements. If such operational procedures cannot be used, then it is recommended that the intermediate channel be

widened by at least 35 ft to allow passing of the two loaded Phase I design ships.

c. It is not recommended that the overtaking area be constructed as tested in the simulation unless the overtaken ship can be slowed to a speed that allows tug control before the overtaking begins. If such is the case, the tugs would have to hold the ship in position throughout the overtaking maneuver and could cause traffic interference and delays. This operational procedure would probably require additional width depending on the size of the tugs used.

HSC Bayou Segment

Based on the real-time pilot results, WES proposes the following channel layouts:

a. The proposed channel width of a minimum of 600 ft for the Phase II (50-ft) project is recommended.

b. Either the Phase I 530-ft channel should be widened to nearly 590 ft (only 10 ft narrower than Phase II) or the combined beams of meeting and passing ships should be limited to less than 260 ft. Realizing the increased difficulty of setting up for a passing situation in the bayou and of controlling meeting situations, it is recommended that the 45-ft Phase I channel be widened to the Phase II width.

c. It is recommended that the reach alongside Spilmans Island continuing through the Baytown Bridge be built as tested in the follow-up testing program (Figure 21) with channel markers suspended from the bridge.

d. It is recommended that the turn at Exxon be built as tested in the simulation program. The recommended channel design in the turn just south of the Exxon terminal may be modified in order to reduce dredging near Alexander Island (Figure 22). Simulation tests indicated that ships should not pass through this area.

e. It is recommended that the turn at San Jacinto be built as tested in the follow-up testing program to more closely follow the existing channel alignment (Figure 23). This modification is predicated upon the straight Goat Island reach east of San Jacinto being built to a Phase I width of 600 ft to allow pilots more leeway in meeting/passing operations. The combined beam limitation of 260 ft may be removed for this and other reaches where the Phase I channel is widened to the Phase II width.

f. It is recommended that the segment of channel between Cargill and Oxy-Chem docks be restricted to one-way traffic for large vessels. However, the channel width here should not be further reduced because

smaller vessels may need to meet there and ships docked at Cargill tend to encroach on the channel.

g. The "straight corner" bend wideners between straight channel segments may be replaced with rounded wideners (Figure 24).

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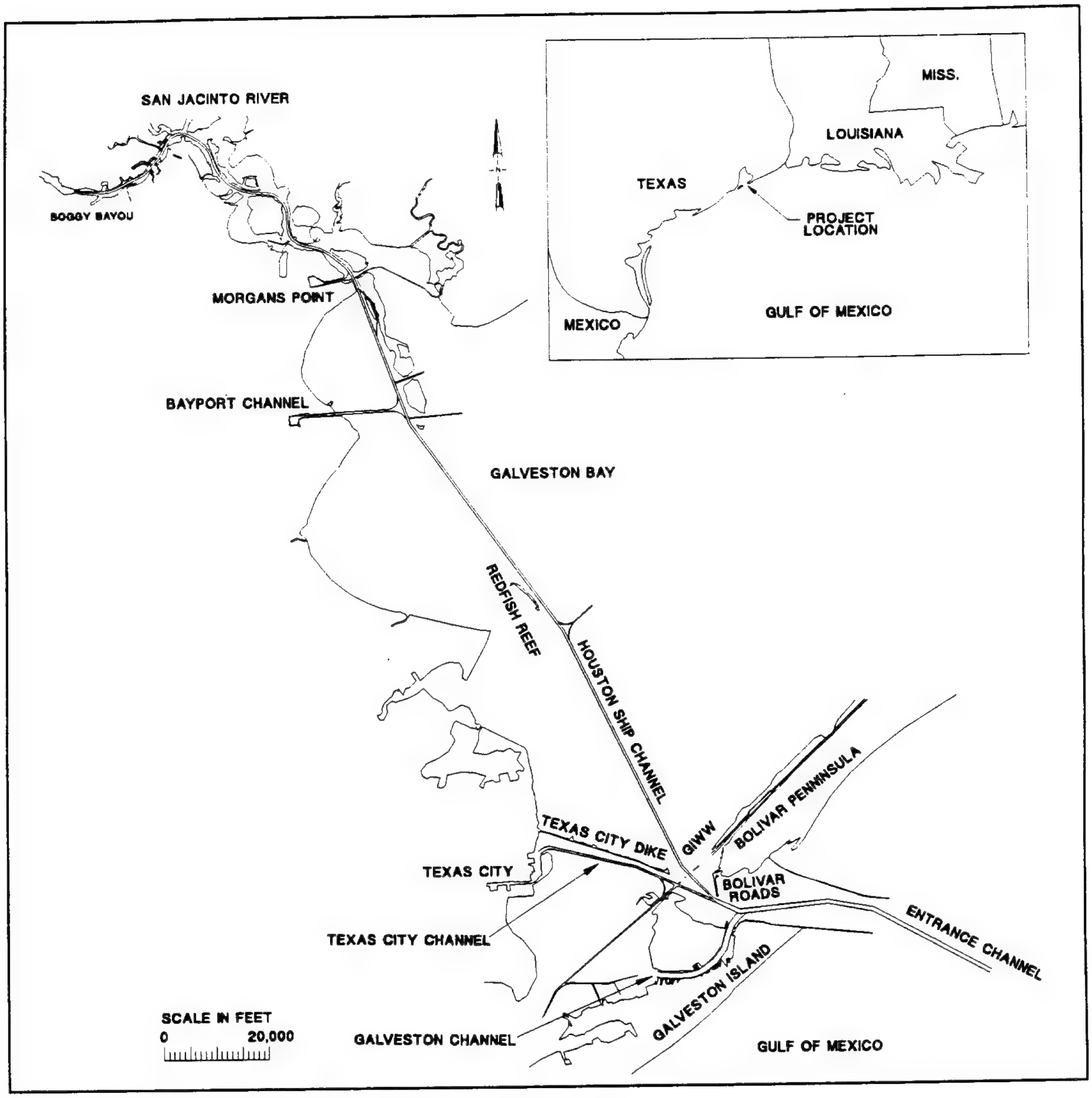

Figure 1. Location and vicinity maps, Houston-Galveston Ship Channels Project

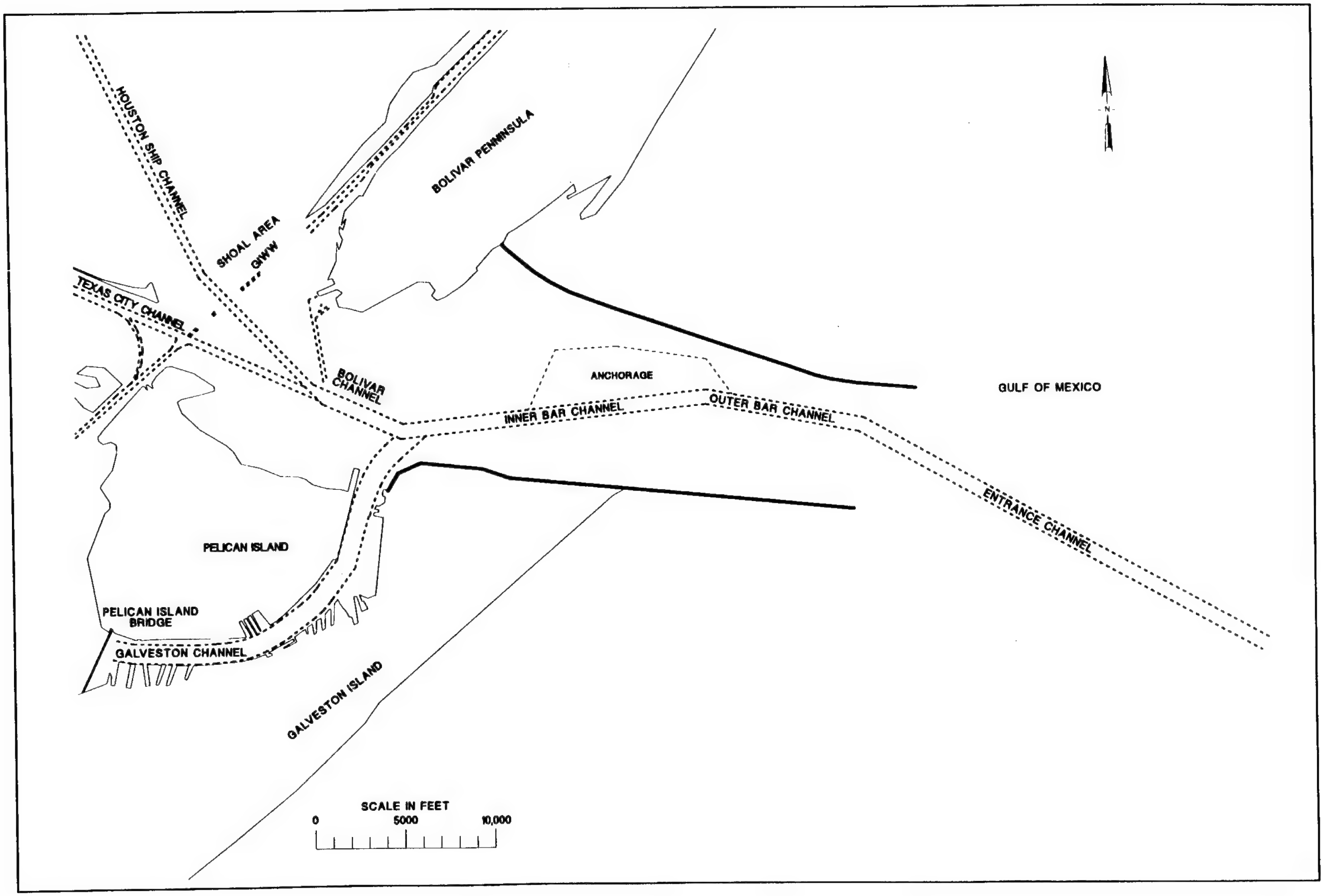

Figure 2. Houston-Galveston entrance channels

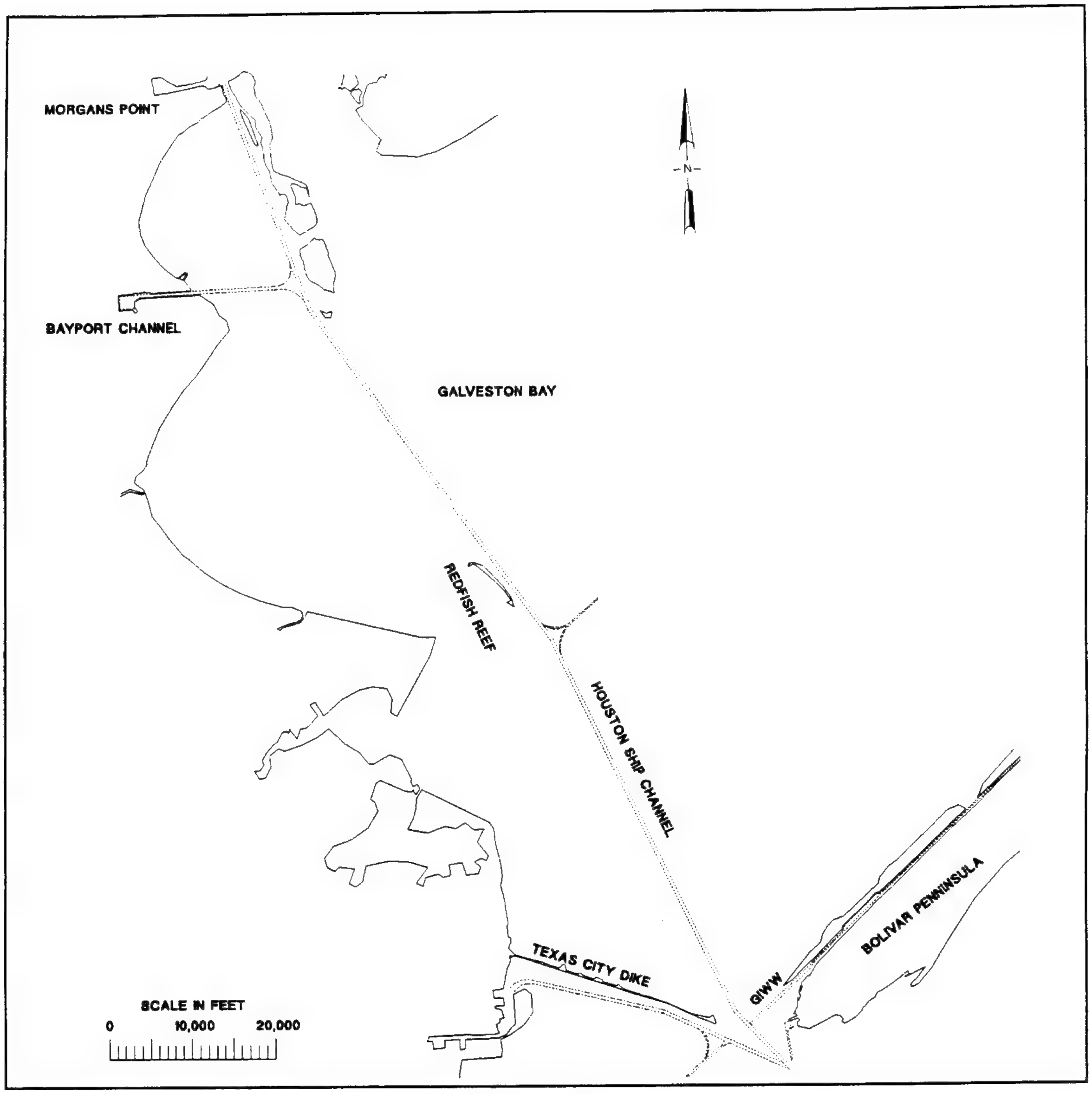

Figure 3. Galveston Bay portion of HSC

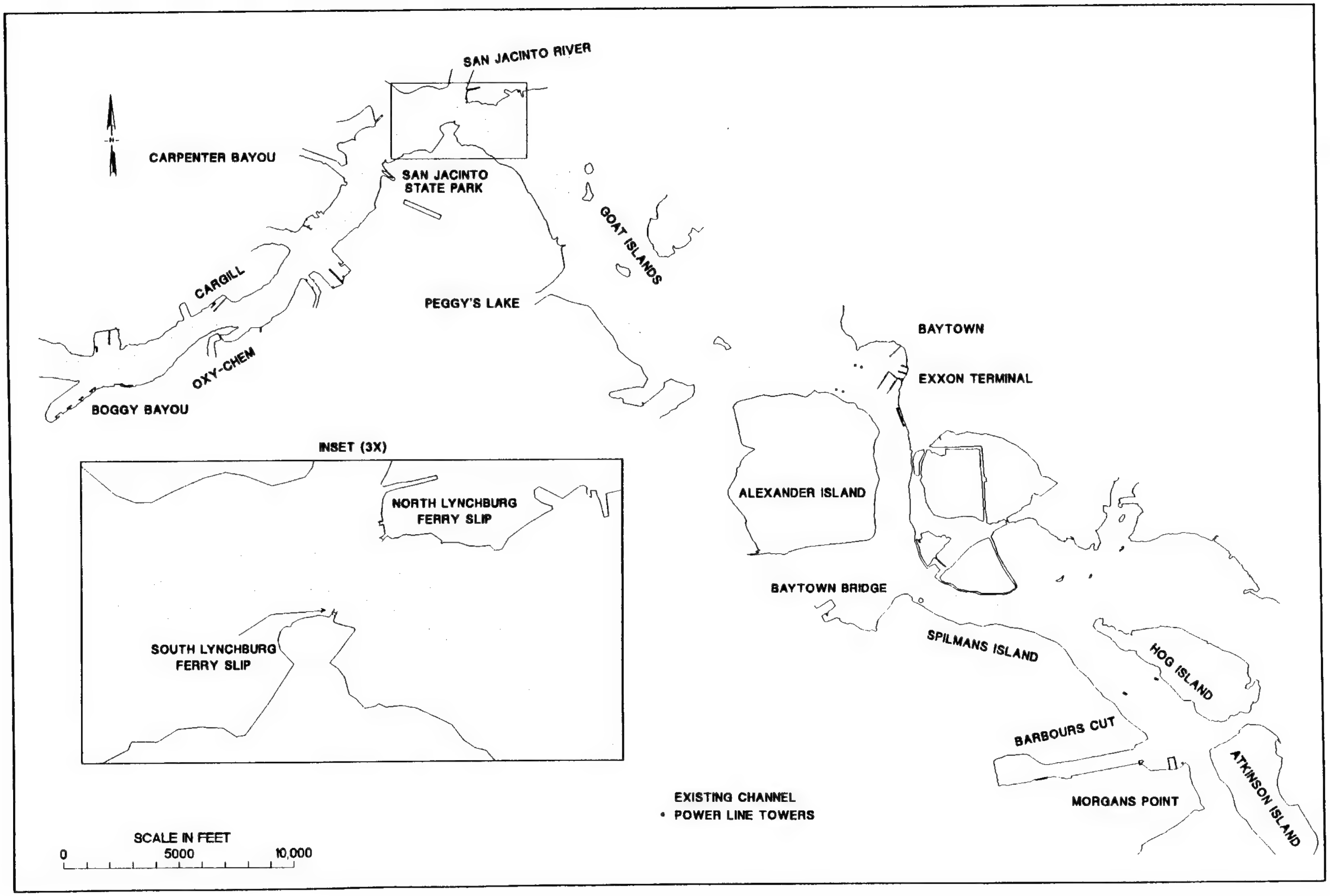

Figure 4. Bayou section of HSC

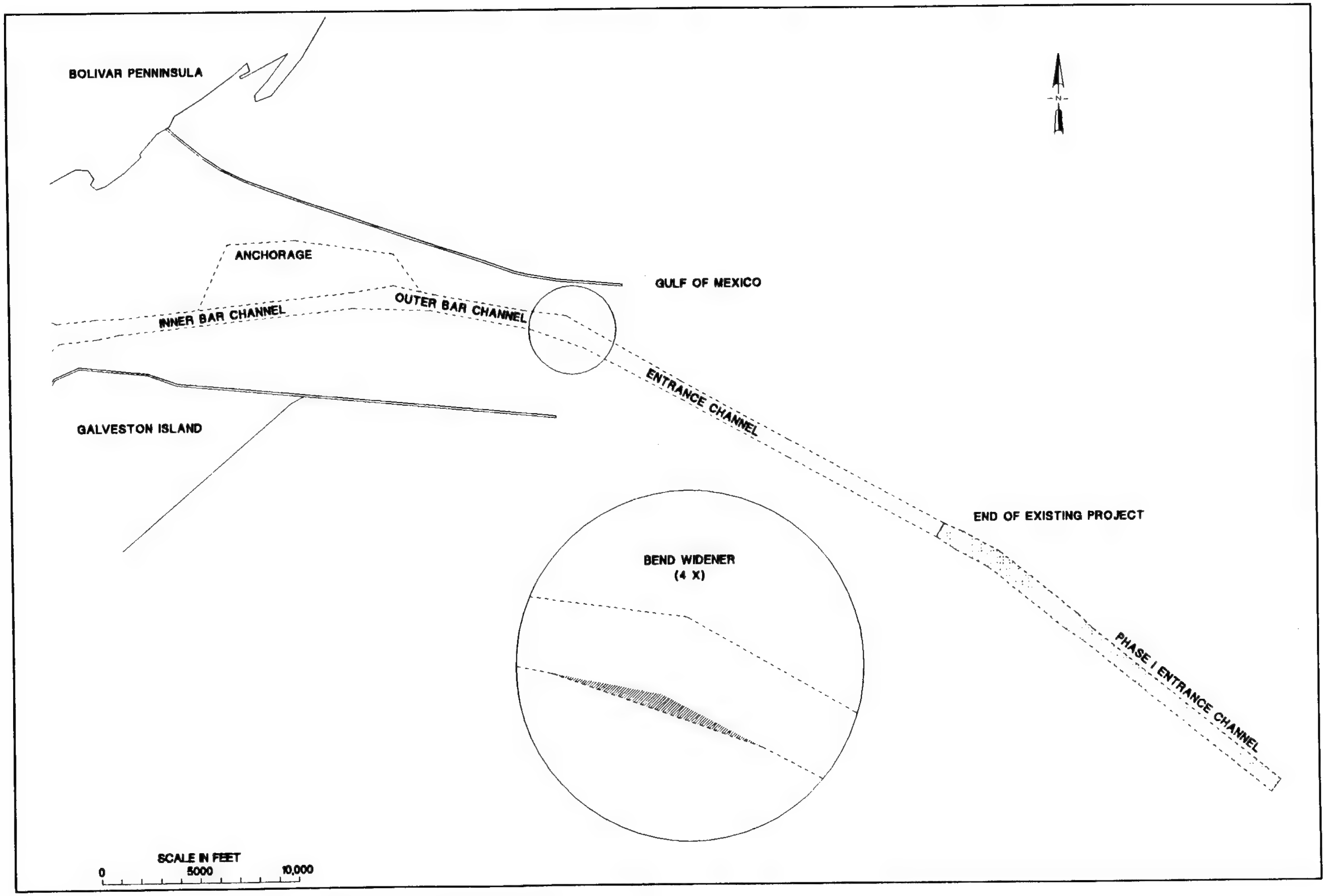

Figure 5. Phase I entrance channel extension

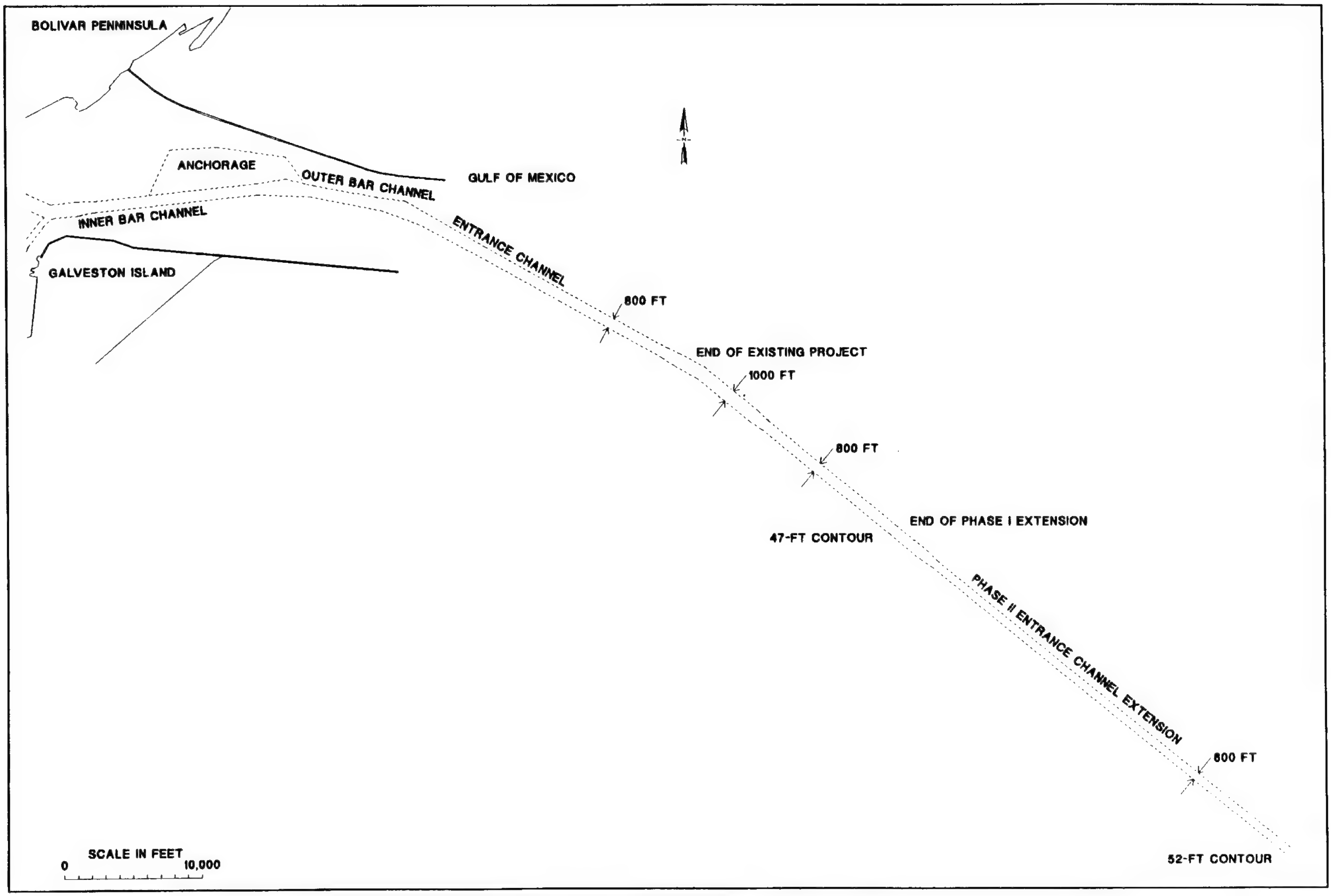

Figure 6. Phase II entrance channel extension

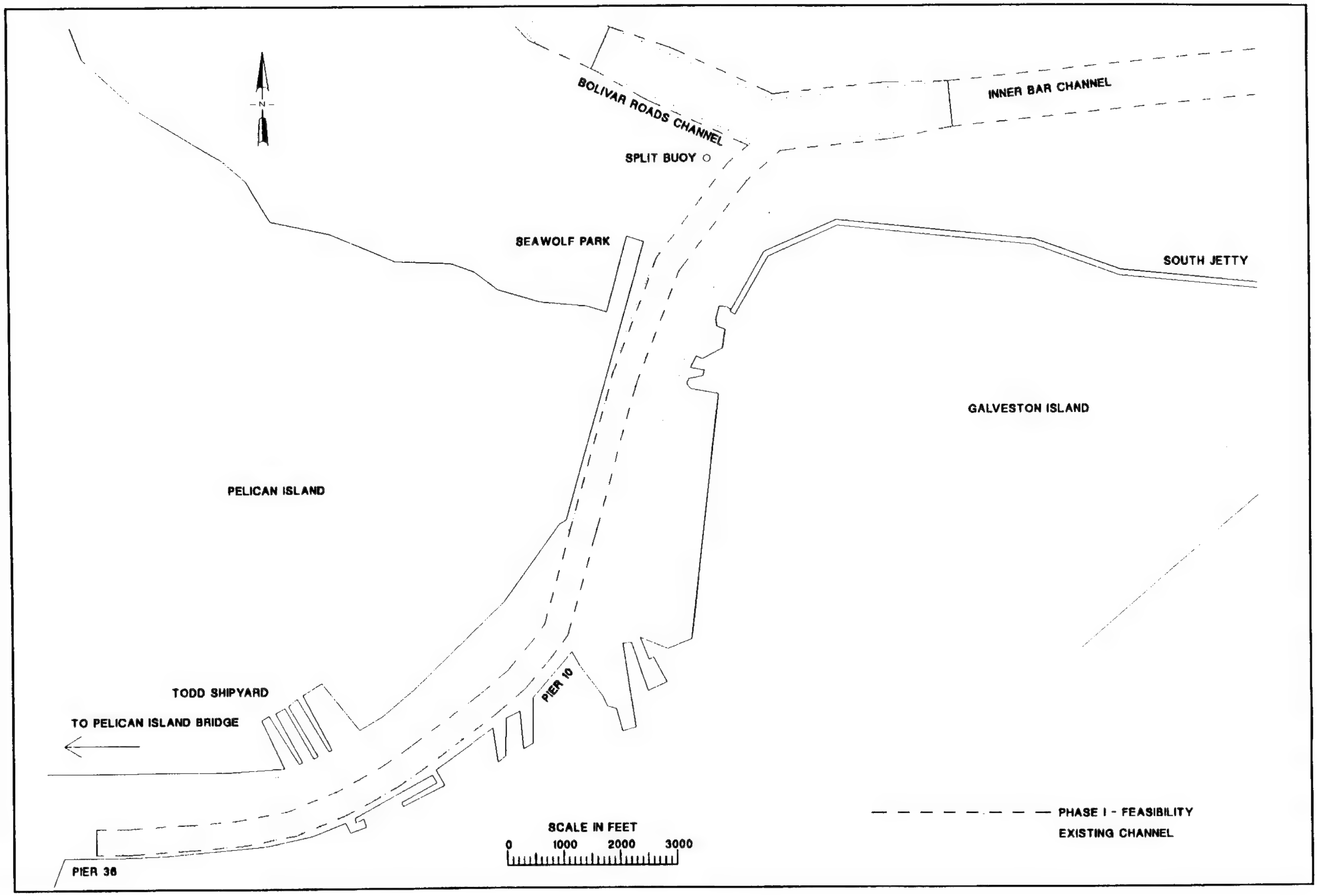

Figure 7. Phase I Galveston Ship Channel (from USAED, Galveston, 1987)

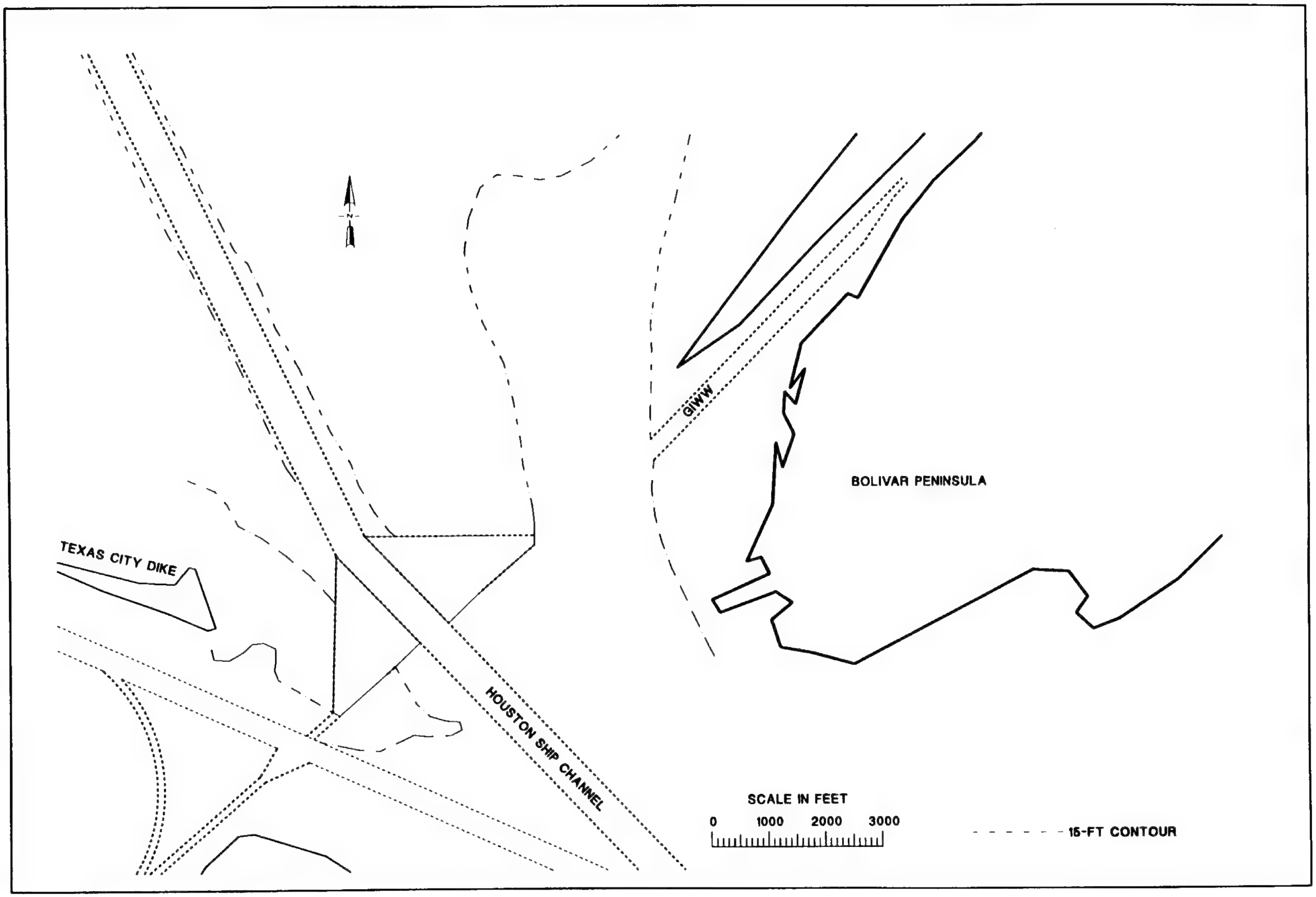

Figure 8. GIWW/HSC intersection (from USAED, Galveston, 1987)

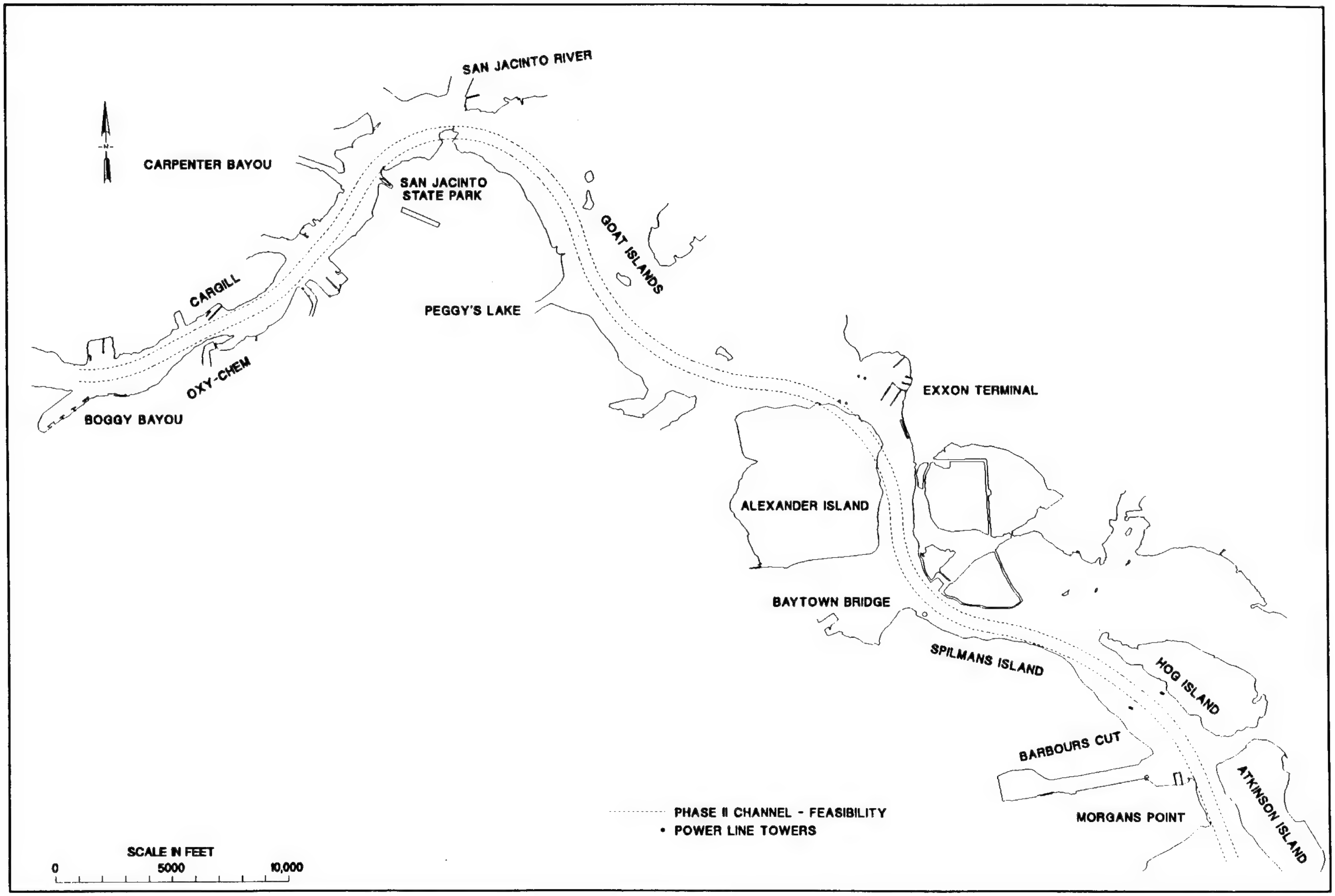

Figure 9. Bayou section channel (from USAED, Galveston, 1987)

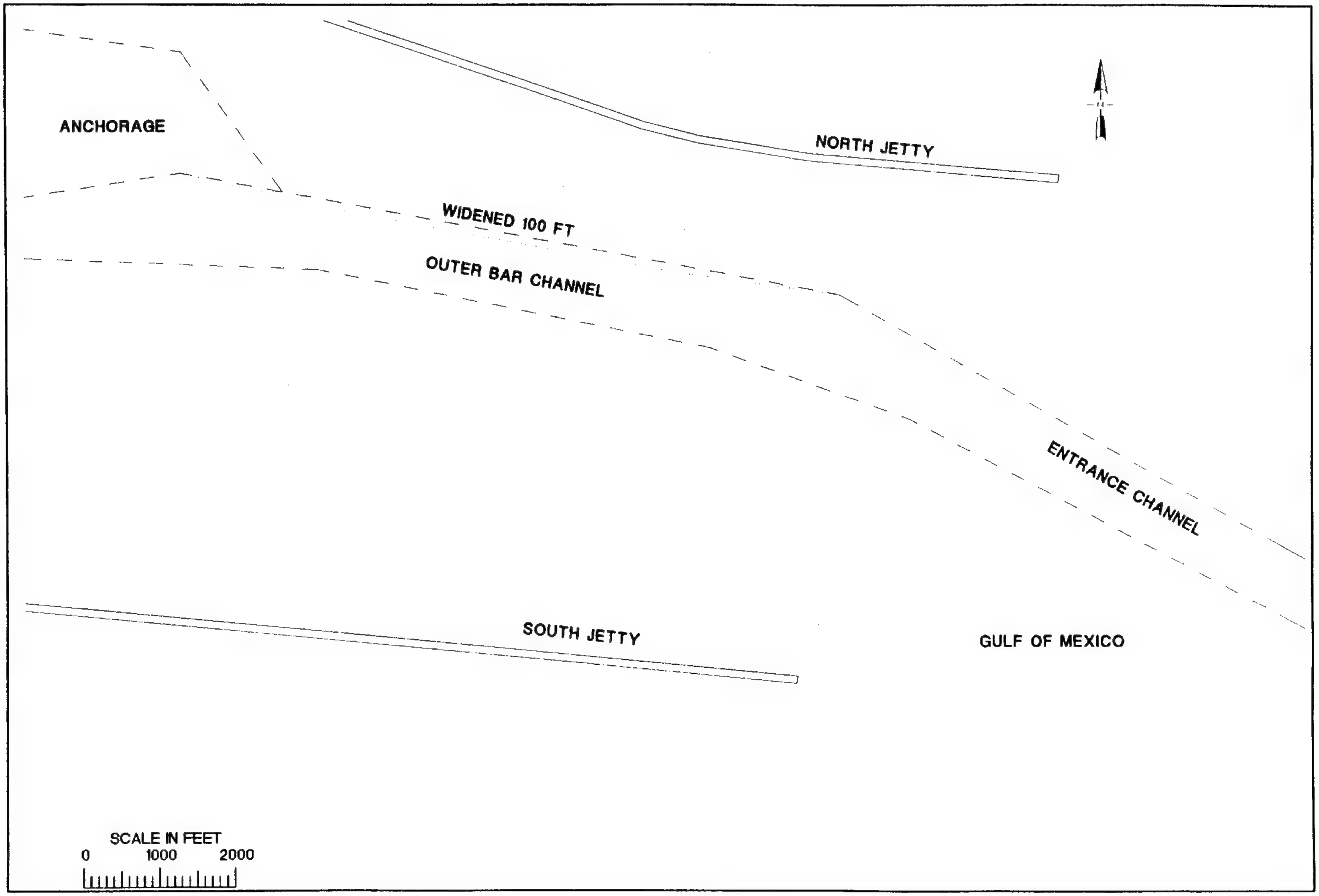

Figure 10. Outer Bar Channel widener

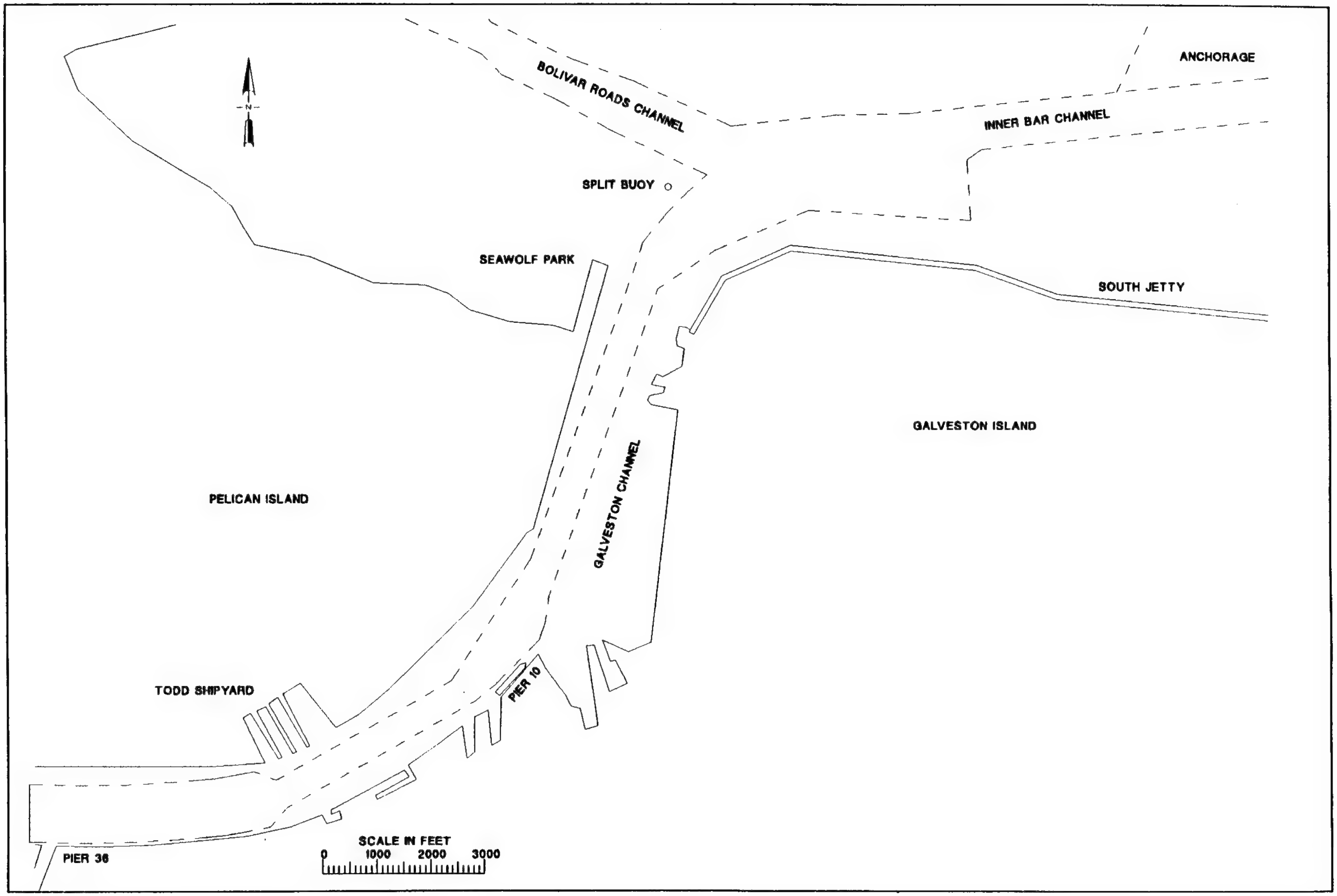

Figure 11. Phase I Galveston channel, as tested

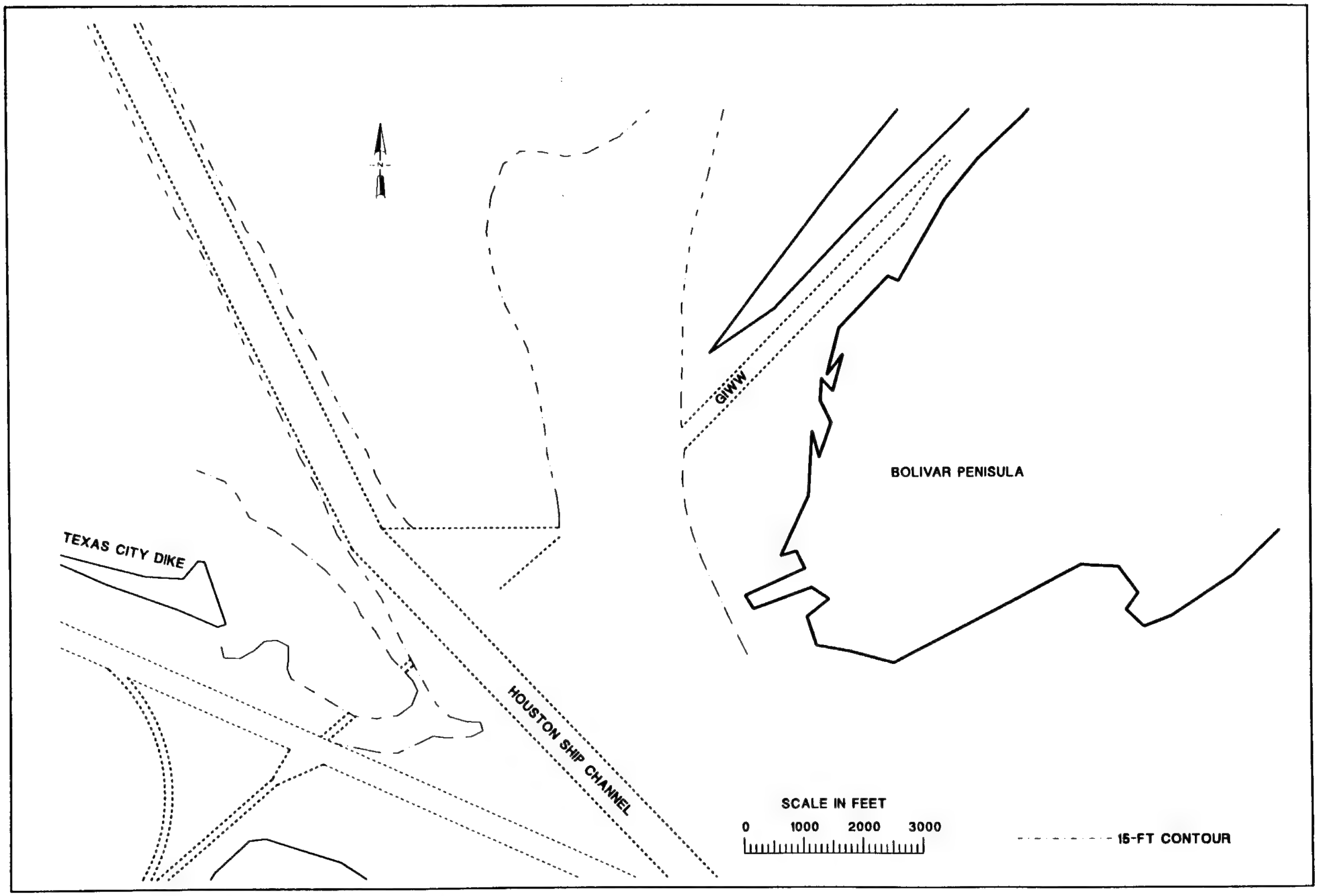

Figure 12. GIWW/HSC intersection, eastern widener only

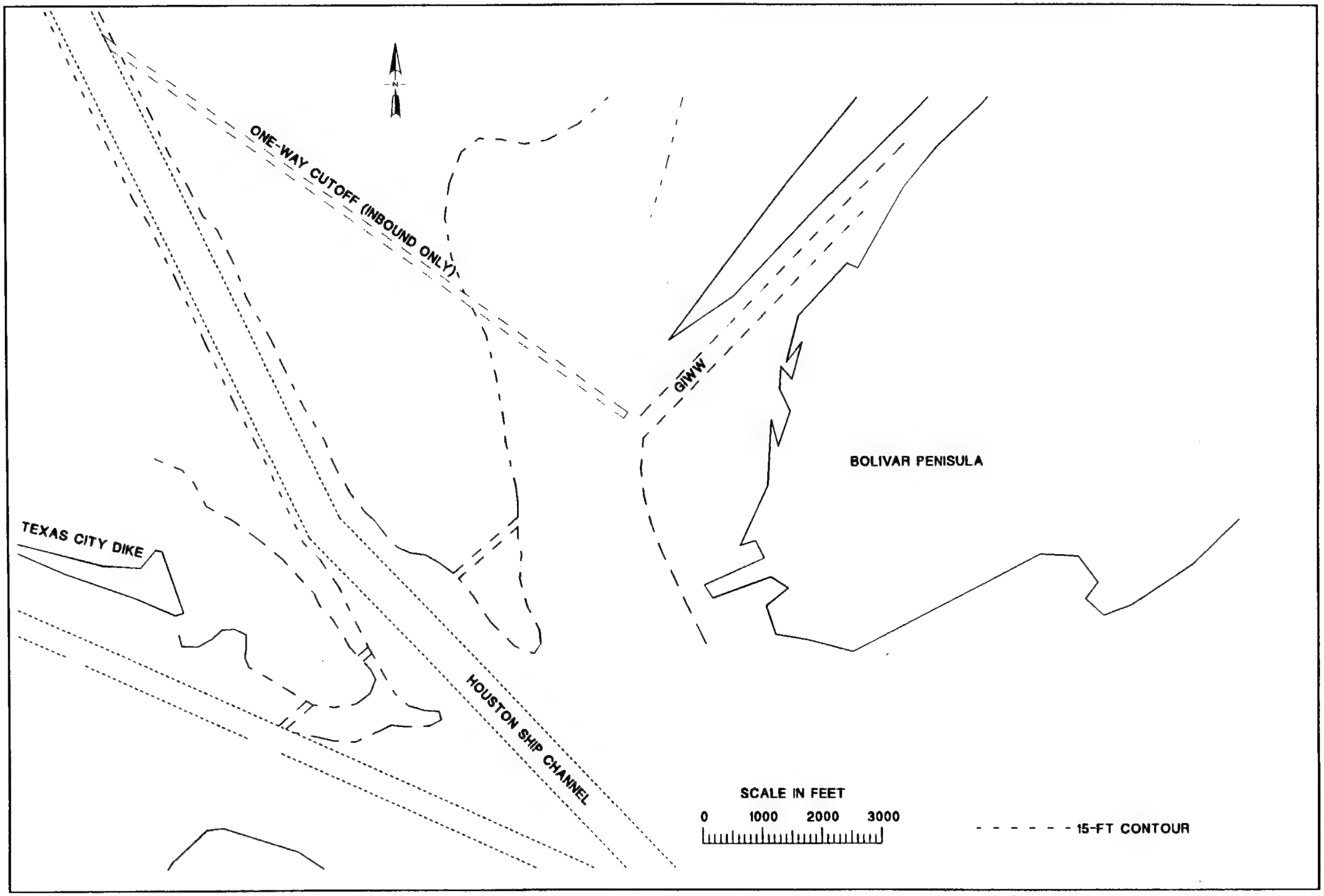

Figure 13. GIWW/HSC intersection, one-way cutoff

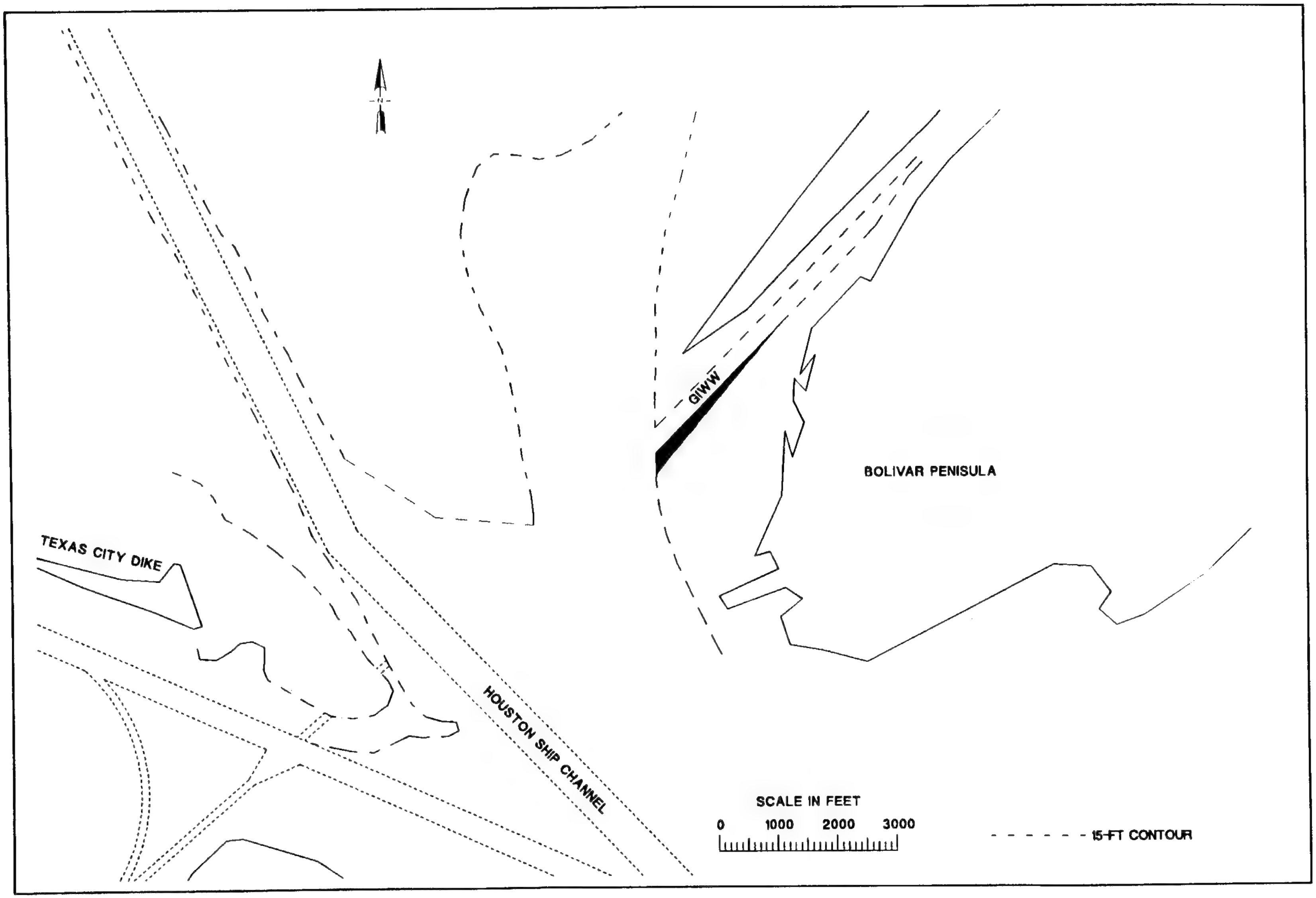

Figure 14. GIWW/HSC intersection, as tested

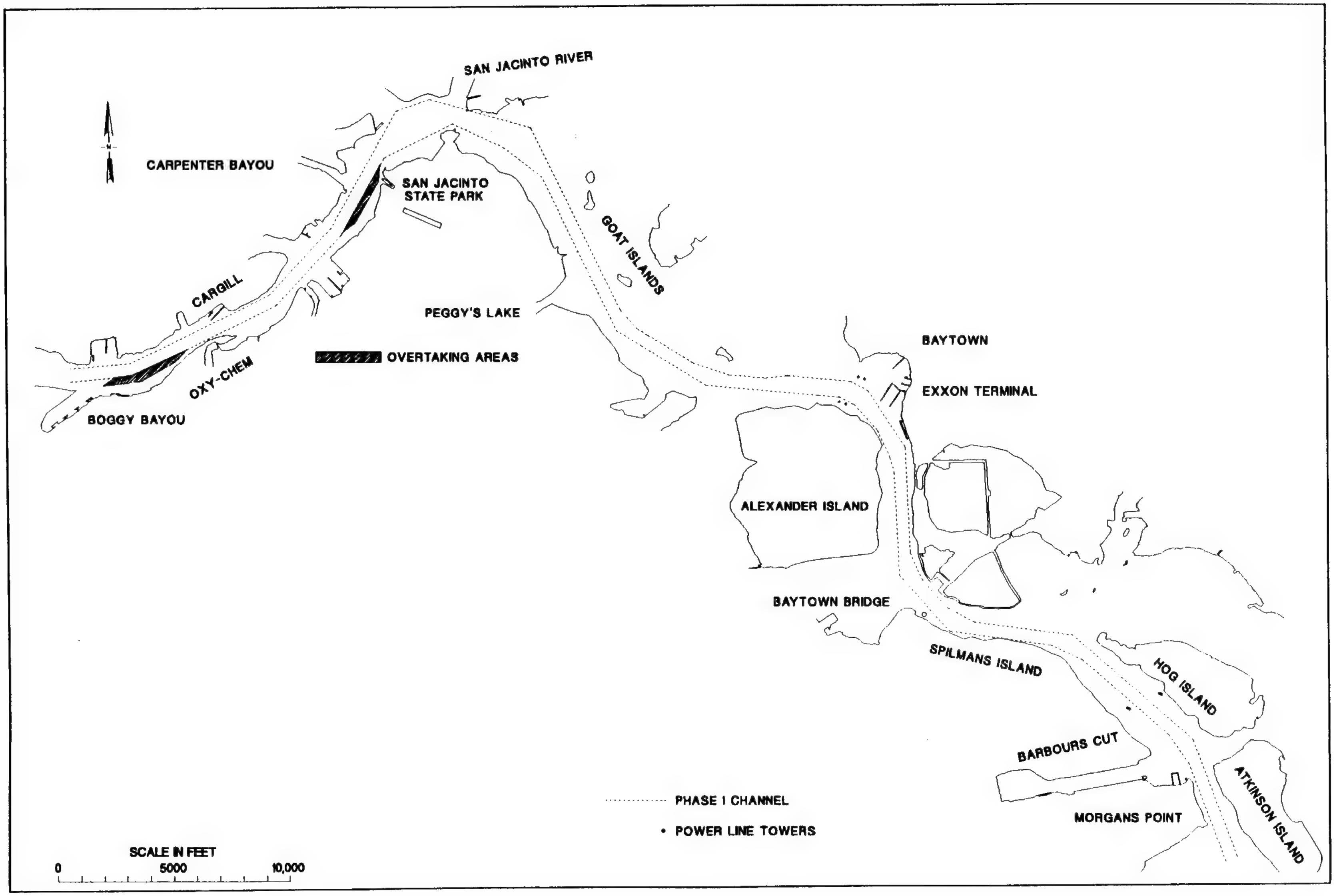

Figure 15. Phase I bayou section, as tested

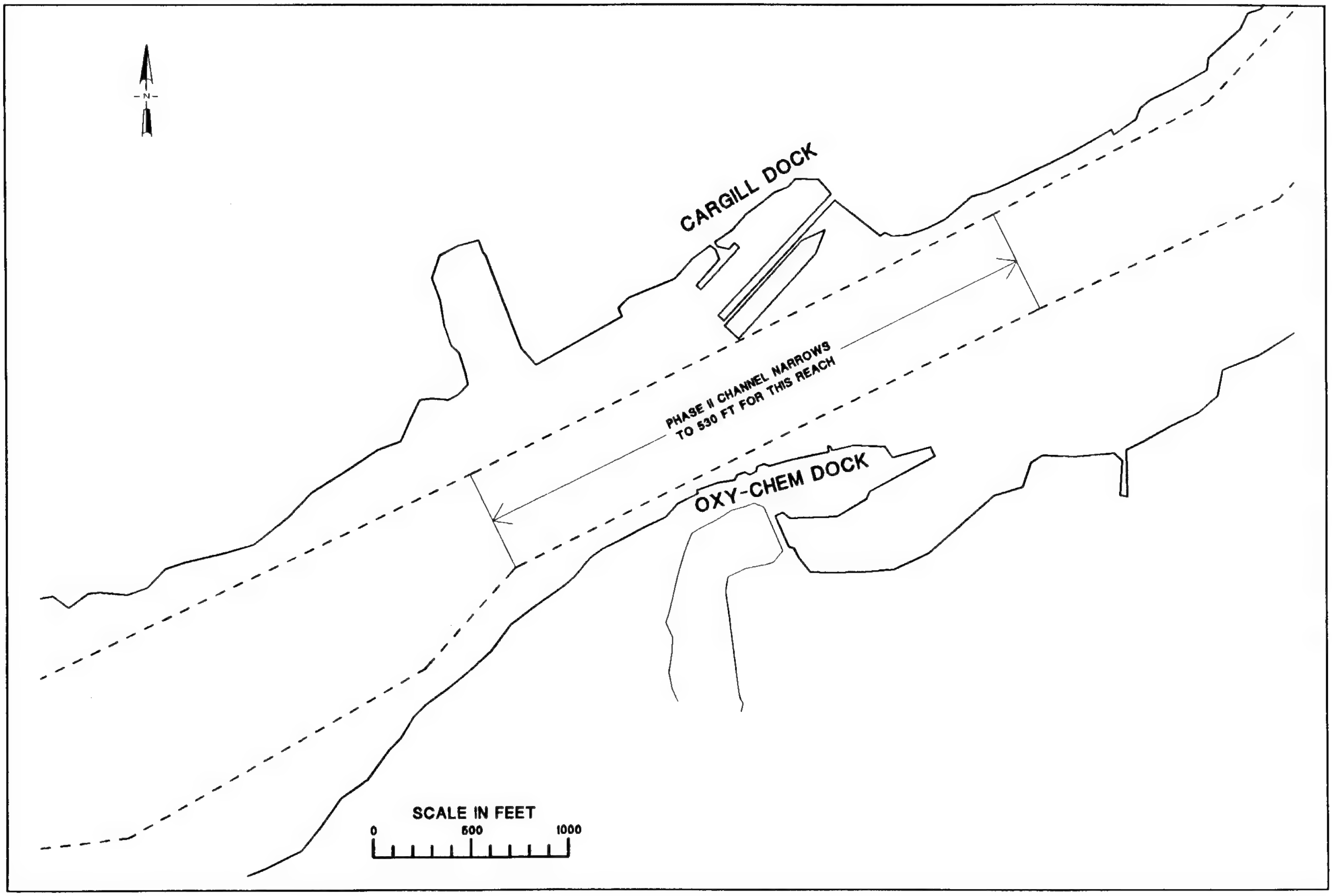

Figure 16. Phase II channel between Cargill and Oxy-Chem docks

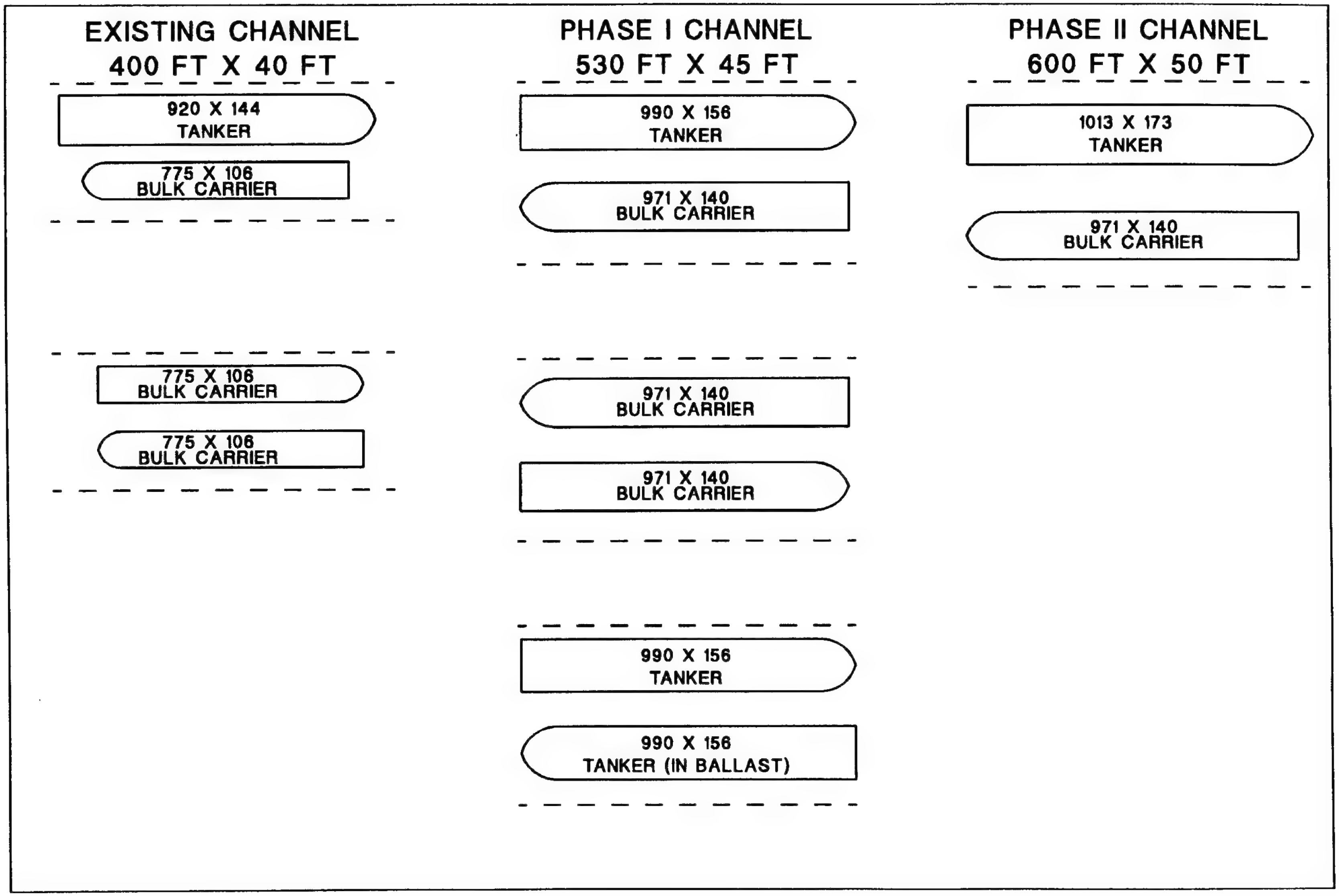

Figure 17. Ship combinations used during simulation of Houston-Galveston ship channels

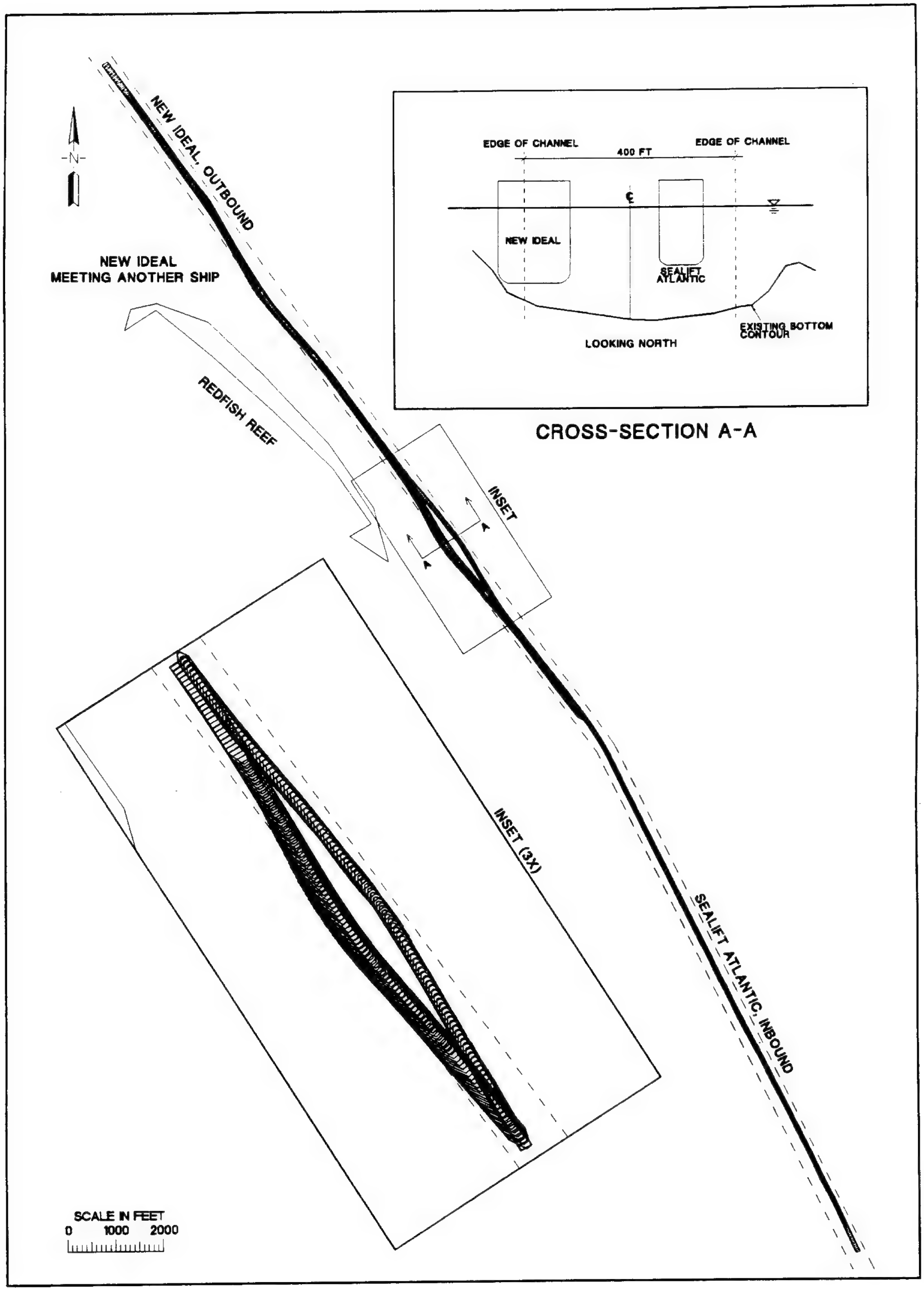

Figure 18. Track plot of DGPS vessels

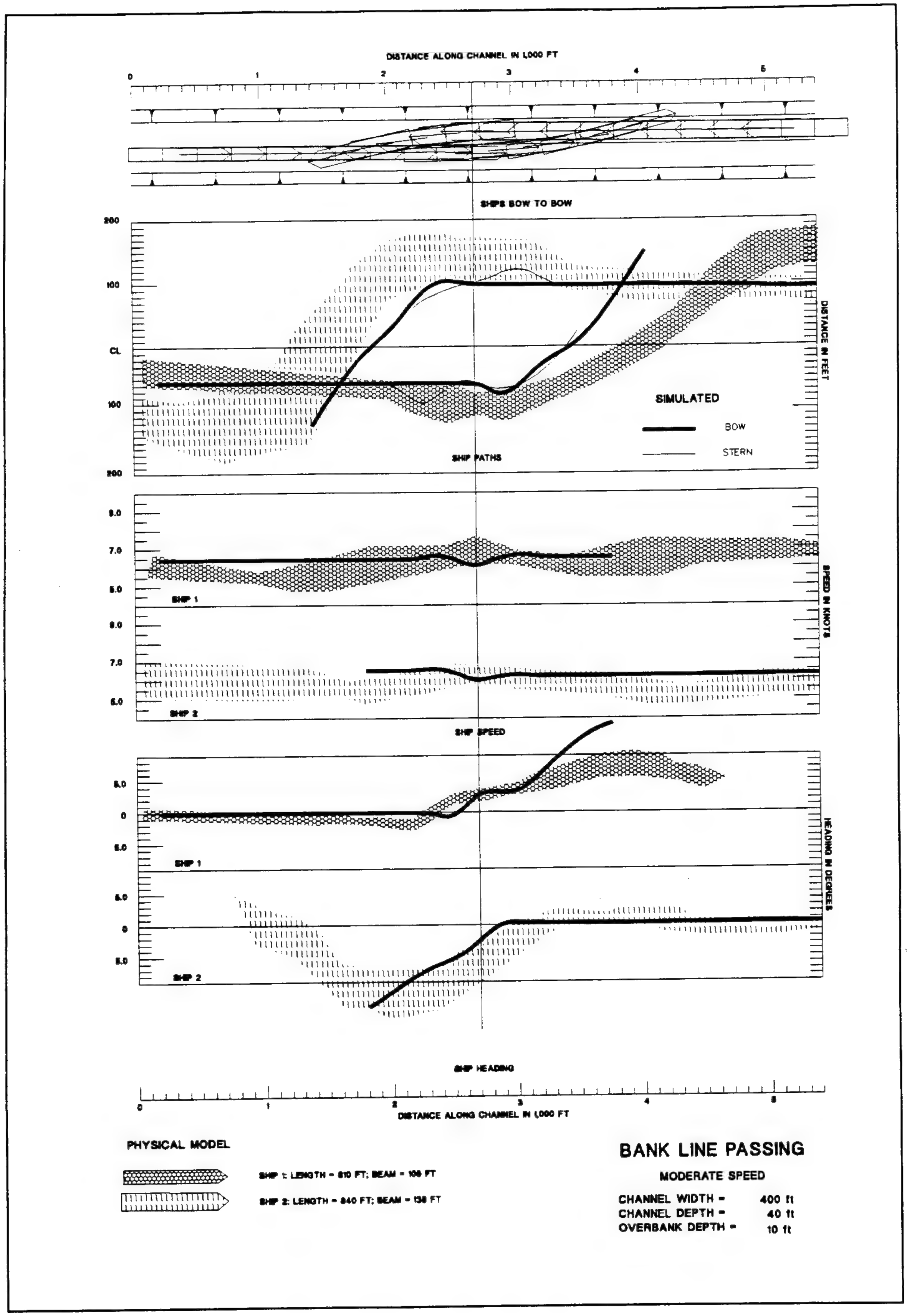

Figure 19. Comparison of physical model and simulator results

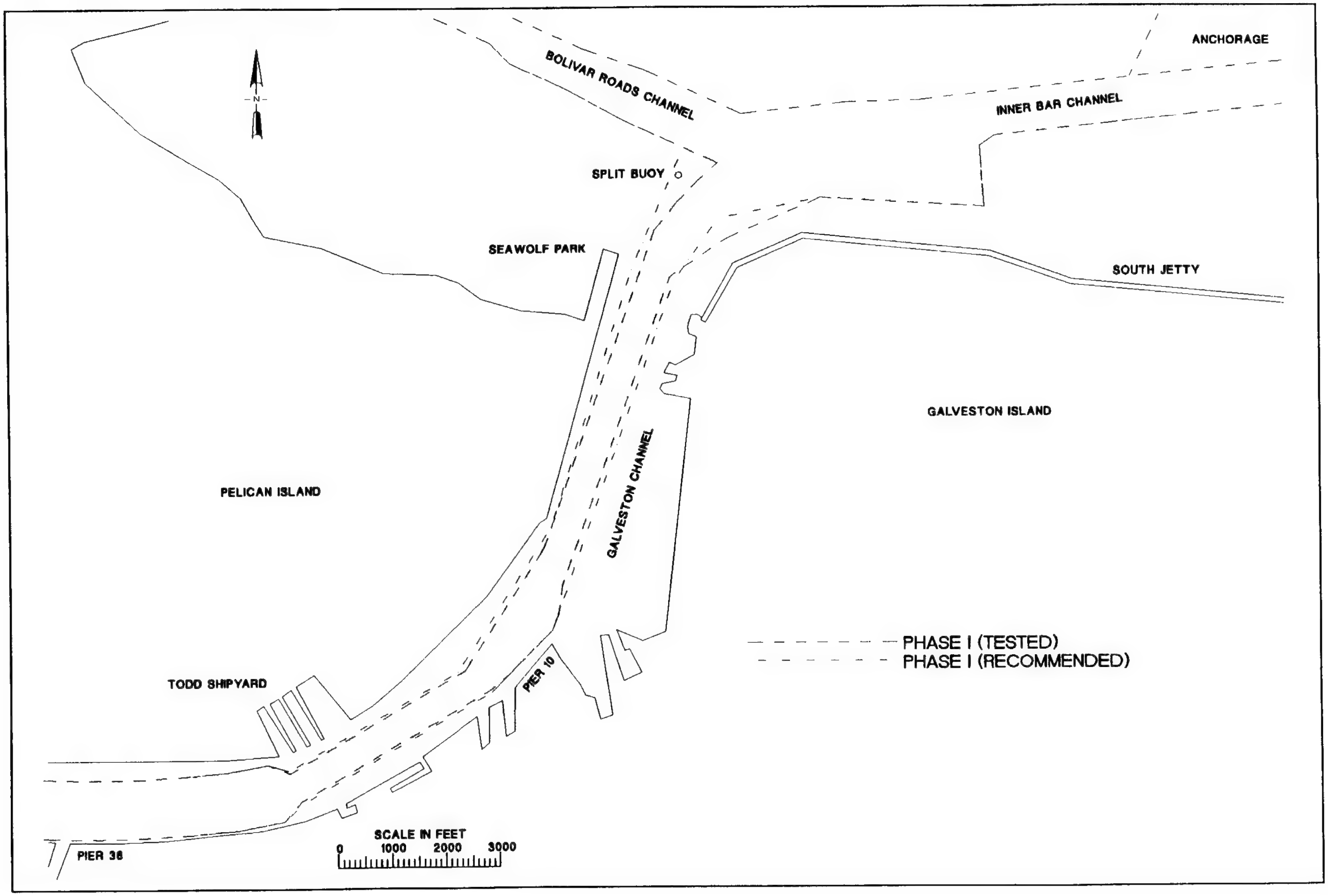

Figure 20. Phase I Galveston channel, recommended

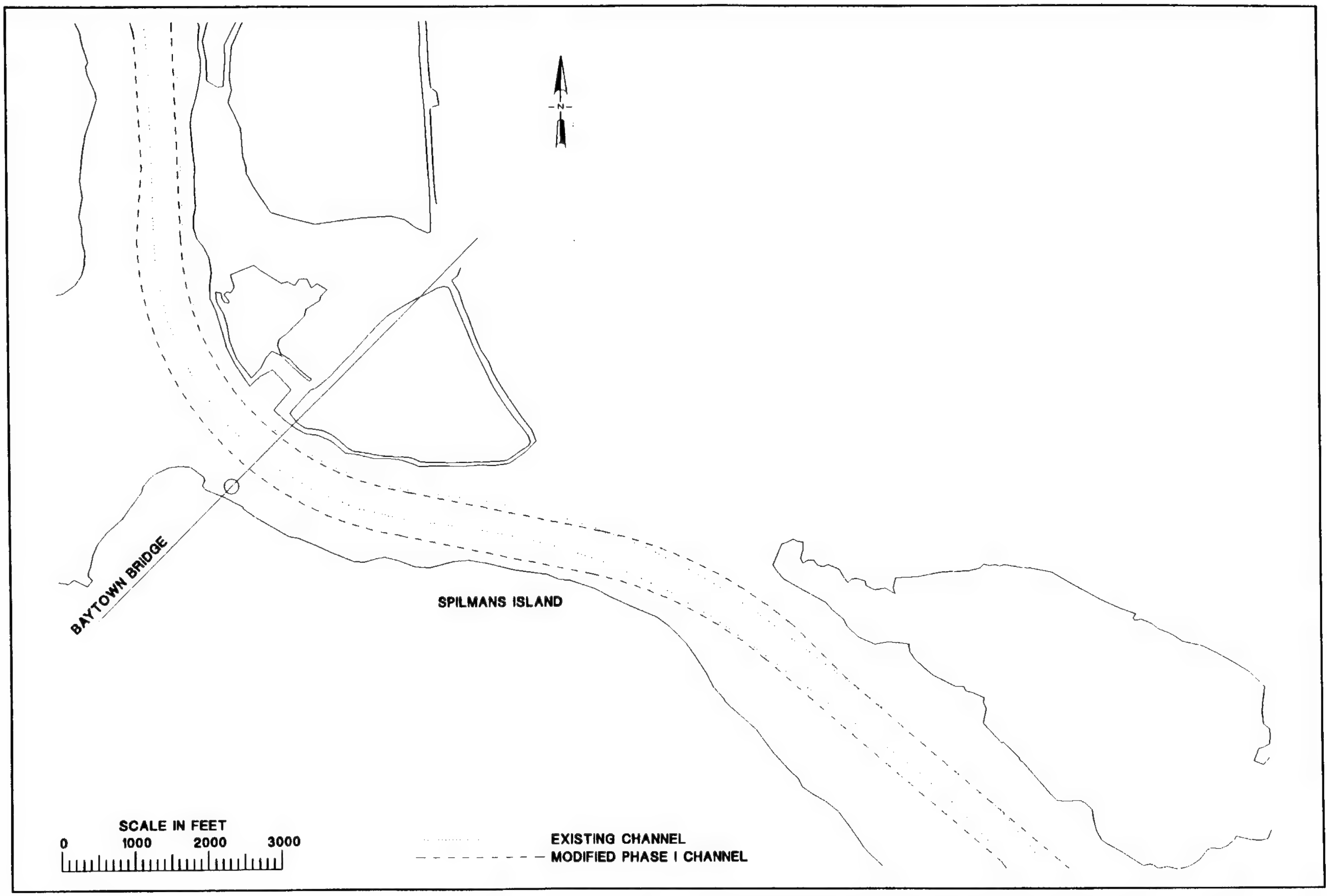

Figure 21. Spilmans Island reach as modified by simulator design effort

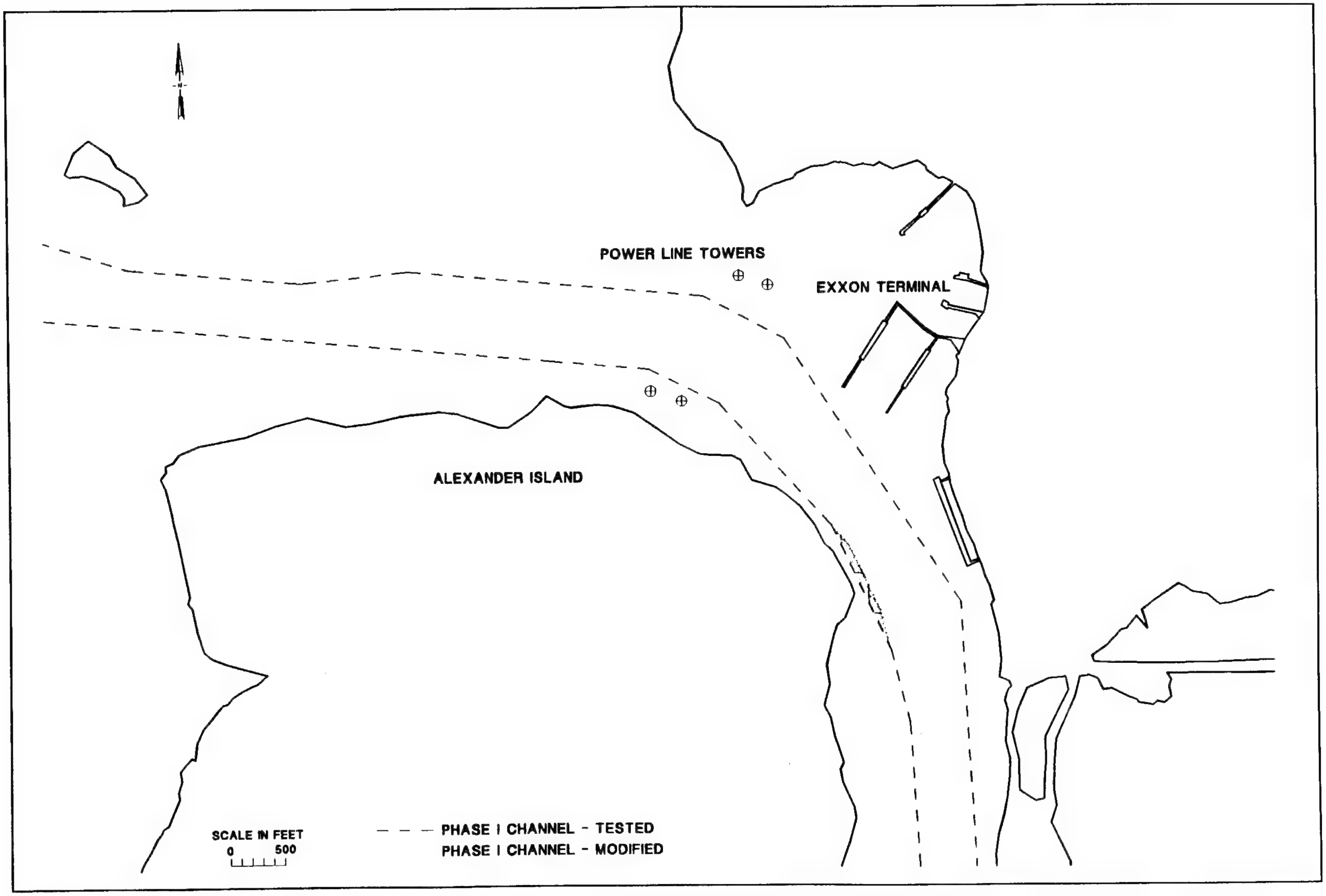

Figure 22. Phase I channel modification near Exxon terminal

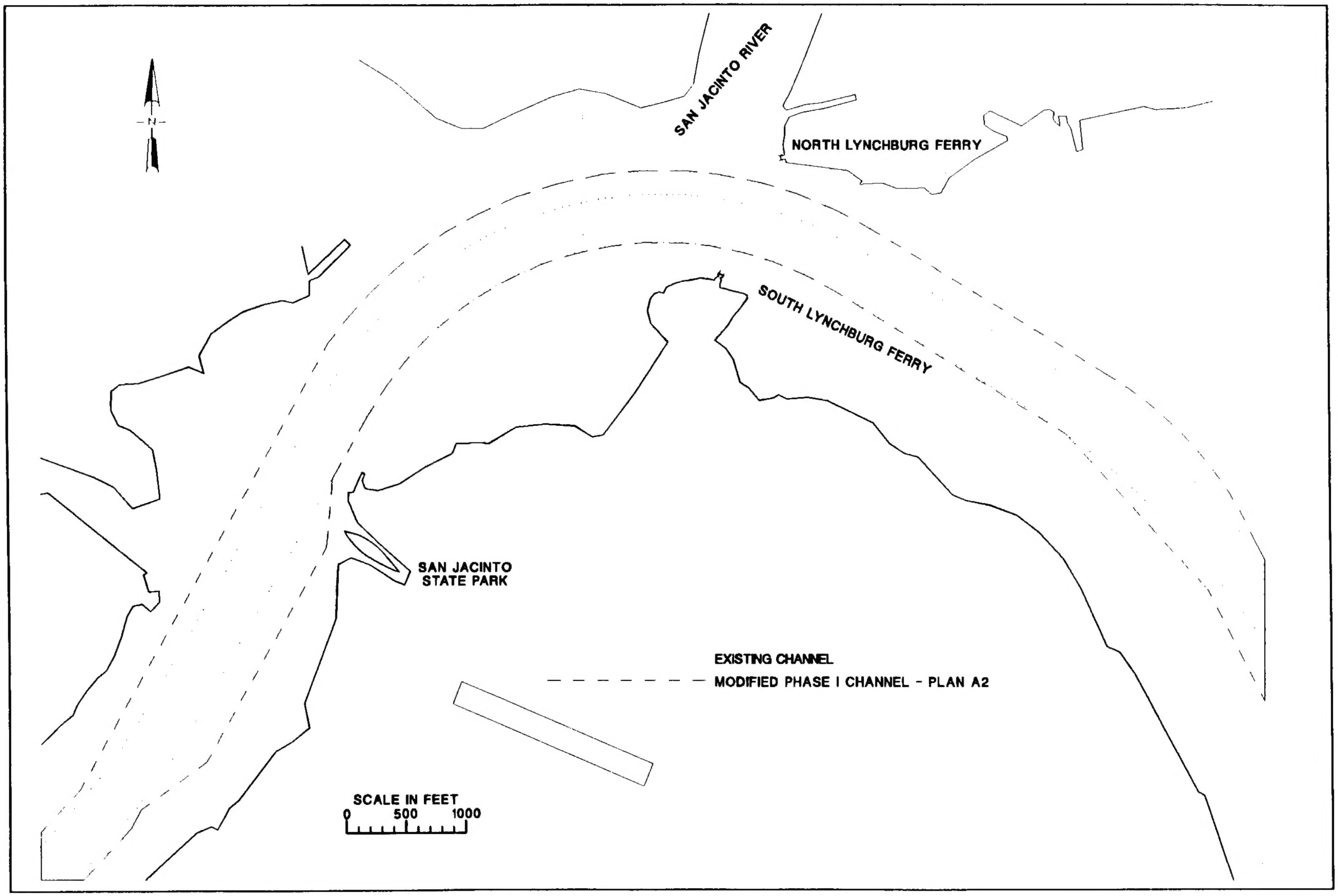

Figure 23. Lynchburg turn as modified during simulator design

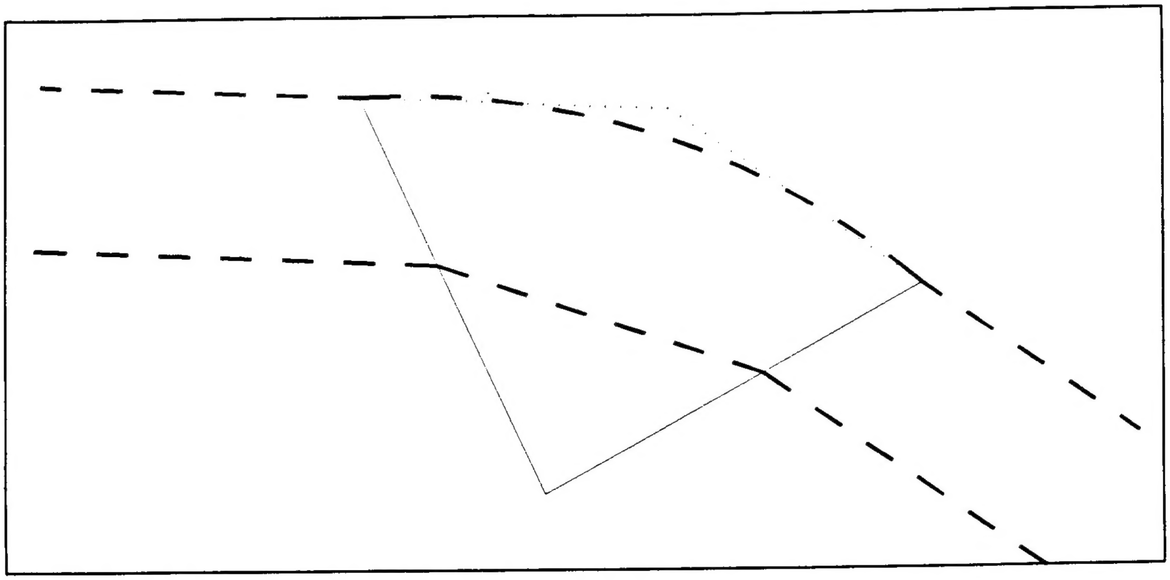

Figure 24. Modified bend widener

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13. ABSTRACT ***(Maximum 200 words)***

This report summarizes the navigation studies conducted on the Houston-Galveston Navigation Channels using U.S. Army Engineer Waterways Experiment Station ship simulator during the period 1991-1993.

The Houston-Galveston Navigation Channels are located along the Gulf of Mexico Coast in eastern Texas. These channels include the Entrance Channel, the Bar Channels (Bolivar Roads Area), Galveston Channel, the Texas City Channel, the Gulf Intercoastal Waterway (GIWW), and the Houston Ship Channel (HSC), which branches off the Bolivar Roads Channel, traverses Galveston Bay, and ends in Houston.

The HSC consists of approximately 65 miles of improved deep-draft channels. The present channel is 400 ft wide and 40 ft deep at mean low tide for most of the channel distance. The project design calls for the channel to be improved in two phases. The Phase I channel is to be 530 ft wide and 45 ft deep, and the Phase II channel is to be 600 ft wide and 50 ft deep. A navigation study was conducted for the Houston-Galveston Navigation Channels, including a real-time ship simulation of the project area, to determine a cost-effective channel design for safe navigation. The Texas City Channel and the section of the HSC past Boggy Bayou are not included in the improvement project.

(Continued)

14. SUBJECT TERMS

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13. ABSTRACT (Concluded).

The HSC is designed for two-way deep-draft traffic. The capability of large loaded vessels to meet and pass is the primary factor in determining safe channel width. In the highly restricted channel, both bank and ship interaction effects are significant factors in conducting bow-on meeting and passing maneuvers. Prototype data and data from a physical model were used to provide guidance in simulating this maneuver. Other considerations in channel design include several sharp turns, strong currents in certain areas, shallow-draft traffic, location of docks and moored vessels, turning basin operations, overtaking area, and channel marking. Hydrodynamic modeling of the bay was a key element of the study and provided currents for the navigation design.